Feasibility Study of Heating and Cooling Solutions for Wuxi Eco-City

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Abstract

Wuxi city has a strong economy and is well located for an eco city project, only 128 km from Shanghai. Wuxi Eco-City is a Sino-Swedish initiative to build an environmentally friendly district. The 2.4 km² area will include residential buildings, commercial buildings, offices and potentially a stadium. A preliminary urban plan has been made, providing housing for 20 000 people. China has a large energy demand and heating in the northern regions is responsible for around 30% of the annual energy usage. A heating solution that is efficient, scalable, sustainable and economical needs to be developed for the eco city to not increase the burden on the system. This report investigates what heating and cooling solutions would be optimal for the eco city, basing its evaluation on the performance, implementability, scalability and risk of the different solutions. A model was constructed for visualization purposes and to create a scenario of what the overall energy usage could be given certain parameters. The GSHP technology is deemed the most appropriate solution for Wuxi Eco-City and the estimated annual energy usage for the scenario was 1822 MWh.

Further economic analyses of the cases when the annual heating/cooling load is low should be made to determine if there are cases in which an ASHP or a VRV system should be preferred. An alternative suggestion is to implement a minor centralized heating and cooling system using WSHPs. Studies should be performed concerning effect on Lake Taihu, economic viability, and expected performance before an implementation.
Sammanfattning

Wuxi har en stark ekonomi och är väl belägen för ett ekostadsprojekt, endast 128 km från Shanghai. Wuxi Eco-City är ett svensk-kinesiskt initiativ för att skapa en hållbar stadsdel. Den 2.4 km² arealen kommer innehålla bostäder, kommersiella byggnader, kontor och eventuellt ett stadium. En preliminär plan över stadsdelens upplägg är färdig och är dimensionerad för 20 000 invånare. Kina har ett stort energibehov, 30% av vilket kan direkt hänföras till uppvärmning av de nordliga regionerna. En effektiv, skalbar, hållbar och ekonomisk lösning är av stor vikt för att inte vidare belasta det kinesiska systemet. Denna rapport undersöker vilken uppvärmningslösning som är optimal för Wuxi Eco-City, baserat på dess prestanda, implementerbarhet, skalbarhet och risk. En modell, skapad i STELLA, utvecklades för visualisering och uppbyggnad av ett scenario för distrikets energikonsumtion. Bergvärmepumpsteknologin anses vara den lämpligaste lösningen att implementeras i Wuxi Eco-City och den uppskattade årliga energianvändningen var 1822 MWh.

Ytterligare ekonomiska analyser av fallen när det årliga värme- och kylbehovet är lågt bör genomföras för att undersöka om det finns fall då en luftvärmepump eller ett VRV-system är mer lämpligt. En alternativ lösning är att implementera ett mindre fjärrvärmesystem uppbyggt av vattenvärmepumpar för värme och kyla. Undersökningar av effekten på Lake Taihu, ekonomisk gängbarhet och förväntad prestanda bör göras innan en sådan lösning.
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<th>Description</th>
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<tbody>
<tr>
<td>ASHP</td>
<td>Air Source Heat Pump</td>
</tr>
<tr>
<td>COP&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Coefficient of Performance (heating cycle)</td>
</tr>
<tr>
<td>COP&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Coefficient of Performance (cooling cycle)</td>
</tr>
<tr>
<td>DH</td>
<td>District Heating</td>
</tr>
<tr>
<td>DHAC</td>
<td>District Heating Absorption Cycle</td>
</tr>
<tr>
<td>DHW</td>
<td>Domestic Hot Water</td>
</tr>
<tr>
<td>DSHP</td>
<td>Dual Source Heat Pump</td>
</tr>
<tr>
<td>DX</td>
<td>Direct Expansion coil</td>
</tr>
<tr>
<td>EER</td>
<td>Energy Efficiency Ratio</td>
</tr>
<tr>
<td>FTX</td>
<td>From-To Exchange</td>
</tr>
<tr>
<td>GSHP</td>
<td>Ground Source Heat Pump</td>
</tr>
<tr>
<td>HSPF</td>
<td>Heating Seasonal Performance Factor</td>
</tr>
<tr>
<td>Δh</td>
<td>Enthalpy difference</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
</tr>
<tr>
<td>SAHP</td>
<td>Solar-Assisted Heat Pump</td>
</tr>
<tr>
<td>SEER</td>
<td>Seasonal Energy Efficiency Ratio</td>
</tr>
<tr>
<td>SPF</td>
<td>Seasonal Performance Factor</td>
</tr>
<tr>
<td>VRV</td>
<td>Variable Refrigerant Volume</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>Flow rate, (m³/s)</td>
</tr>
<tr>
<td>WSHP</td>
<td>Water Source Heat Pump</td>
</tr>
<tr>
<td>Q</td>
<td>Heating/Cooling load</td>
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1 Introduction

1.1 Background

Chinese government officials were inspired by Sweden’s Hammarby Sjöstad to create sustainable districts (Cederquist, 2013). Wuxi is a City near Shanghai with considerable economic activity and one of the locations for such a project. This led to an initiative between Swedish institutions and the Chinese government for an eco city covering a 2.4 km² area of land on the outskirts of Wuxi (Stoltz, 2013). The project is officially called The Wuxi Sino-Swedish Eco City, but is from now on referred to as Wuxi Eco-City.

The district area has a mild and humid climate (Jiangsu.net, 2012). It is, however, in need of heating during the winter (Zhou et al, 2008). The eco city will therefore be in need of both cooling and heating solutions, preferably combined into one compound solution.

A heating and cooling solution should be versatile and adapted to the local conditions. Through a study of the performances of different solutions, with a scalable simulation for visualization, the most viable solution for Wuxi Eco-City can be found.

1.2 Research Questions

The main questions guiding this study were:

- What heating and cooling solutions are possible within Wuxi Eco-City?

- What parameters affect the feasibility of the different solutions?

- What factors have to be examined before implementation of the suggested solution?

1.3 Aim

The aim of this project is to evaluate the most favorable heating and cooling solution for residential and commercial buildings in Wuxi Eco-City and construct a model for visualizing the general energy demand.
2 Methodology

This report is based on data from a literature review and case studies. Information is gathered in order to examine possible heating and cooling solutions, compare them, and provide a suggestion for implementation.

The data is compiled and examined, and relevant properties of the technologies are set in contrast to each other. An evaluation is made and the technologies are given individual ratings.

The solutions given the lowest ratings are disregarded as possible solutions and the remaining solutions are further evaluated out of a sustainability perspective (the “Sustainability Triangle” perspective).

Lastly, a suggestion for implementation is given alongside with examples of investigations that have to be performed before implementation. Suggestions of future research within this area are also given.

In parallel with the research of possible solutions a model in the simulation software STELLA is constructed. This model will display the differences between the possible solutions, though only as an illustrative tool, in this report. A model scenario consisting of the suggested solution will be presented to give an example of the total energy demand using this solution.

2.1 Assumptions

2.1.1 Assumptions related to the report

- The data from the market available HPs is not completely accurate as to the actual performance of the HP.

The market data gathered on the performance of the heat pumps is varying. The units in which the performance is measured can be interpreted differently and the methods of investigating the performance are not reliable in all of the perceived cases. The data will be taken into consideration if and where it can be deemed as realistic and representative.

In Sweden, the ground properties’ only affect the depth at which drilling needs to be made (Berglund, 2013), the same is assumed for China.

2.1.2 Assumptions related to the simulation

- The weather data received represents a typical year.
- The heat pump is not turned off over the nights.
- The heat pump is turned off during working hours (since the simulation only covers residential buildings)
- The heat pumps are assumed to have a fixed value of thermal efficiency.
- The same dimensioning principle as in Sweden is used in China.
- The GSHP (Ground Source Heat Pump) has a performance that can be approximated as constant, one COP₁ and one COP₂ (presented as SPFs in the evaluation).
- The WSHP (Water Source Heat Pump) has a performance that varies but, due to lack of data, is approximate by a constant SPF for each mode.
- The change in COP due to the temperature difference, for VRV (Variable Refrigerant Volume) and ASHP (Air Source Heat Pump) technologies is linear and 3% per 1°C change.

- The Swedish dimensioning principle is assumed applicable to China.

The attained weather data is deemed as reliable as an approximation as well as the policy of not turning of the heat pump during the night; this would impinge on the comfort of the home. The model assumes a perfect correlation between heating/cooling demand and the heat pump output. Over a year the possible divergences from this estimation can be assumed to even out due to the heat pump giving too much output during certain times and then too little at others. The Q data provided contains assumptions as to the behavior of the inhabitants of the apartments. This includes turning of the heat pump when leaving for work and turning it on when coming back home. This is based on the assumptions by Engdahl & Wallgren (2013), and can be regarded as behaviors that are based on perceived habits. The assumption is easily altered in the simulation.

Most of the solutions require dimensioning when implemented into the buildings. The same principle as in Sweden (95-97.5% of total annual demand) is applied in order to maintain the thermal comfort of the buildings.

The performance of the ground source heat pump (GSHP) is considered to be constant. The ground temperature will not vary significantly, given adequate spacing between pipes (Bohdanowicz and Johnsson, 2005). This will cause the performance to be relatively constant.

The water source heat pump (WSHP) has a varying performance depending on the temperature of the source. It is however smaller than the variation displayed by the typical air source heat pump (ASHP) (Chen et al., 2006). For simplification, the performance of WSHPs is therefore assumed to be constant. It is assumed that the SPF (Seasonal Performance Factor) values attained will provide an accurate estimation of the performance.

The change in the COP values for the ASHP and Variable Refrigeration Volume (VRV) system can be approximated as linear and to be circa 3% per 1°C change (Madani, 2013).

2.2 Limitations

2.2.1 Limitations concerning the scope

The scope of the report will be limited to finding the best heating & cooling solution for the residential and commercial buildings, excluding domestic hot water (DHW) supply. The case studies investigated reflect different implementations, both small scale and large scale.

The economics of the solutions will not be discussed in detail but rather in a wider perspective, only treated by rough estimation in the evaluation of the technologies’ feasibility. The uncertainty regarding factors such as electricity prices, cost of borehole digging and prices of water filters is of a magnitude that discourages any economic evaluation in this report. Further studies regarding the aforementioned issues will be suggested in this report.

2.2.2 Limitations concerning the modeling process

The model will simulate the general energy demand that results from using each technology for three different building standards (high end, good standard and Chinese standard).

The commercial buildings sector will be discussed but not simulated. The data available as to the performance of the buildings is limited to residential buildings. Therefore a model for the
assessment of the energy usage in commercial buildings will be developed but not utilized in this report.

2.3 The Sustainability Triangle

The sustainability triangle (See Fig. 1) consists of the three aspects: economical, environmental and social.

These forms the basis of sustainability, if one is lacking then the solution is not considered sustainable through time. The concept of sustainability permeates the report and functions as a guiding principle throughout the report. The final suggestions will take into consideration the parameters of the sustainability triangle.

![Image of the Sustainability Triangle]

**Figure 1 - The Sustainability Triangle. It consists of the three aspects: economical, environmental, and social (Munasignhe et al, 2013)**

2.4 Systems Thinking

In assessing the energy demand for heating and cooling in Wuxi Eco-City and finding the best solution to meet this need, ‘systems thinking’ is going to be implemented. According to Donella Meadows, author of the book ‘Thinking in Systems’, a system can be defined as “A set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors…” (Meadows, 2008). Systems interact with each other. There can be small systems and large systems, systems within systems and systems that contain many different systems. Meadows emphasizes that it’s difficult to find anything that can’t be described as a system.

In this report, operations will be carried out within certain system boundaries (See Fig. 2). These boundaries will aid in defining the issue as well as how it is meant to be handled.

Wuxi Eco-City can be considered as a system that contains many smaller systems such as heating/cooling supply, electricity supply, waste manage, and transportation. It will also contain systems like residential and commercial buildings, which require heating/cooling depending on their properties. In this report the heating and cooling system is the focus. This system is dependent on the properties of other systems such as the buildings, the ground and water conditions, and the policy of the Chinese government.
A testament to the difficulty of the system element/boundary condition classification task is the district heating system of Paris. The subway tunnels were used when setting up the pipe network that distributes the heat (Madani, 2013). Although, without the subway the tunneling for the pipe network would have increased the costs of the project and changed the profitability, including it in the model of the heating system would not have been justifiable beforehand. The feasibility of using the subway system for the network could not have been known before extensive investigation. The linkages between systems, like in this example, are the most difficult to discover (sometimes almost impossible) and it’s therefore important to set the system boundaries right, not too broad, in order for them to fit the current purpose (Meadows, 2008).

Except for facilitating the discovery of mutual dependence between systems, the thinking in systems is also referred to in the hopes of that it will facilitate the work of creating a STELLA simulation. It is important to understand which data is required in order for the simulation to reflect reality and what parts of the system this data affects. The systems thinking approach will assure that the model is a good representation of reality.

Systems thinking has been a guiding approach for formulating the problem.

2.5 Conceptual Model

The conceptual model (See Fig. 2) is a method for visualizing what lies within the system and what the boundary conditions that affect the success of the system are. This displays how system thinking is implemented throughout the report.

Figure 2 - Conceptual Model. For the heating/cooling system in Wuxi with system boundaries.

In the case of Wuxi the climate and conditions (area, access to bodies of water, quality of water and so on) are of key importance when investigating which technologies compose the optimal solution. The water and earth qualities can affect the feasibility of the WSHPs and GSHPs.
Similarly the social acceptance for the technology should be considered. The Social acceptance should however not be a major issue since ASHPs (make slight amounts of noise when on) are prevalent in China (Shigong, 2013). Social factors also include potential obstructions that the heat pump technologies could cause. For instance, the usage of ASHPs on roofs takes up space that could be used for greenhouse or relaxation areas (Thornton, 2010). Social factors will be discussed within the sustainability triangle section of the report.

Building characteristics will affect the solution of choice. Tightly spaced buildings might cause thermal encroachment if using GSHPs (Verda et al., 2012) and the collective demand will affect the feasibility of district solutions.

Biogas or Solar electricity produced in the vicinity could affect what energy carrier the solution would use as input.

2.6 Parameters & Variables

2.6.1 The parameters that affect the recommendations

- Performance,
- Implementability,
- Scalability
- Risks associated with the technology.

Given that the intent is to create an eco city the considered solutions are required to be clean technology. Furthermore, the performance affects the amount of energy consumed (generally produced from coal in China (IEA, 2009)) when the technique is providing the desirable indoor climate.

The performance (together with the implementability parameter) assesses, by proxy, the economical aspect of each solution. The performance affects the amount of energy consumed, which translates to money for running the machine. It also translates to the amount of carbon being emitted during the electricity production.

The implementability shows with what ease a certain solution could be implemented (touching upon the social aspects). This takes into consideration the drilling of boreholes, the laying of thermal mats on lake bottoms, the laying of piping networks and so forth. It also takes into consideration the degree to which the technology is adaptable to different climates and environments.

The scalability determines to which degree the technology can be implemented on both large scale and small scale. This includes building size, size of the system layout, and the total effect.

The risk parameter attempts to quantify the chances of disadvantageous occurrences associated to the solution.

These four parameters cover the three aspects of the sustainability triangle (Social, Economical and Environmental). The social aspect is considered but less applicable. The heat pumps tend to make a certain level of noise; this potential inconvenience can however be decreased through certain simple measures and is otherwise more or less the same for the different solutions, apart from district heating/cooling systems. The remaining solutions will then be evaluated individually from the sustainability triangle perspective.

In this report, less focus will lie on the economical aspect, based in part on the difficulty of attaining such information as energy prices, installation costs and supplier costs.
2.6.2 COP vs. EER

COP is Coefficient of Performance and is used as a tool to compare heat pump performances. It is defined as the ratio between heating, or cooling, output and energy usage for the heat pump. Usually it is denoted by subscript 1 or 2 to distinguish between Heating COP (index 1) and Cooling COP (index 2). It is widely recognized that COP$_1$ usually is about COP$_2$+1 (Madani, 2013).

COP is measured at a fixed set of temperatures and criteria. This causes difficulties to compare between manufacturers and models if they are measured according to different standards. Two common measurement standards for heat pumps are EN14511 and EN255. EN14511 takes the circulation pump into consideration and has a feeding temperature of 45°C whilst EN255 doesn’t consider the circulation pump and has a feeding temperature of 35°C. When possible, it’s favorable to examine and compare heat pumps using the seasonal performance factor (Thermia, 2012).

On some occasions manufacturers choose to use EER (Energy Efficiency Ratio) as an equivalent to COP$_2$. This causes confusion since it’s not calculated in the same way. EER is calculated using British Thermal Units per hour (Btu/h) over energy usage in kW, causing the EER to obtain different values than COP$_2$ (Madani). Moreover, the usage of EER becomes increasingly confusing when users denote the heat pump heating performance by COP and heat pump cooling performance by EER. Considering this, only COP$_1$ and COP$_2$ will be considered as valid performance measurements in the case studies as a part of this report, except in special cases where it is clear how the conversion from EER to COP can be made. If the EER is used correctly, according to its definition, the translation is obtained by dividing the EER by 3.413 (Bureau of Energy Efficiency of India, n.d.).

2.6.3 Seasonal Performance Factor

The Seasonal Performance Factor (SPF) is the average performance of a heat pump over the entire working-season. The measurement is defined as the total output over the total energy usage for the season. It is more accurate than the COP or EER, since these are only evaluated in one point of operation. The SPF will vary depending on the climate and local conditions, therefore two or more SPF values can be achieved for the same machine if in different climates. (Heat Pump Centre, n.d.). The SEER is the equivalent of the SPF for the EER measurement.

2.7 Model construction

A model was constructed to visualize the performance of the different heat pump technologies and to construct a possible scenario for the annual energy demand of the heating/cooling system in the residential district of Wuxi Eco-City. The model, and sensitivity analysis, is further described in Section 4 “Simulation Methodology”.

2.7.1 Sensitivity analysis

A Sensitivity analysis was performed on the factors that affect the COP of the each of the different technologies. This is in order to measure how the performance varies with variations in the assumptions built into the model. These are considered to be the parameters of interest.

For the results of the sensitivity analysis see Appendix B.
3 Literature Review

This section provides an overview of Wuxi and the issue at hand. Following a short description of these boundary conditions, that define the Wuxi-specific part of the challenge, a summary of possible technologies available will be presented. The section is concluded with research concerning actual implementations of the technologies, in form of case studies and data from market available products.

3.1 Wuxi City & Climate

Located in the Jiangsu province and south of the Yangtze, Wuxi lies within one of the wealthiest region in China. It has been called “Little Shanghai” due to its booming economy and fast urbanization. The city is situated in the middle of the Yangtze delta, near the shore of Lake Taihu, and in close proximity, 128 km, to Shanghai (Shanghai Focus, n.d.).

The city has around 6.2 million inhabitants and a GDP growth rate of 13.1%. Amongst the many industries in Wuxi are textiles, electronics, iron, steel, IT and now also solar energy equipment. Home to China’s largest textile cluster, 4 of the top 5 companies in Wuxi are in the textile business (The China Perspective, n.d.). These factors are a likely reason as to why Wuxi was chosen as location for the eco city.

Wuxi has an annual average temperature of 15° C with long frost-free periods of circa 230 days (Jiangsu.net, 2012). The climate is humid and warm, displaying a large cooling load in summer and a milder heating load in winter according to a report by Zhou et al. (2008). According to a report by Chen et al. (2010) the heating and cooling load is fairly similar over the year with a slight overweight towards cooling demand. The actual realized load will likely depend largely on the building properties.

3.1.1 China’s Policy and Regulations considering Central Heating

The south of China can get cold during the winters, amplified by the high humidity. It is known that cities such as Shanghai, Nanjing and other cities south of the Huaihe and Yangtze rivers are uncomfortable during the wintertime (Almond et al., 2009). The past winters have been increasingly colder, causing uproar amongst the inhabitants whom now call for the same benefits as the northern regions where the population benefit from, in many cases free, central heating (Shigong, 2013; Almond et al., 2009).

The Chinese government built the existing heating network between the 1950’s and 1980’s. Due to budget constraints, the heating network was limited to the north of China. The border was drawn at the Yangtze River, Huaihe River and the Qinling mountains (Almond et al., 2009). The buildings sector consumes over 30 % of China’s total energy usage (Ruhang and Yunna, 2012). A large part of it is consumed in the north partly because of an inefficient heating system (Xiaojie, 2013). At the time when the system was built heating was seen as a basic right of the citizens, which led to the government providing free and unlimited heating for the north of China between the 15th of November to the 15th of March. To date, many homes and offices continue to receive free heating. This heating policy is most likely yet another contributing factor as to why the energy utilization in the north is so high (Almond et al., 2009).

Building a similar system in the south to compensate for the colder winters would increase the energy usage of China and be less efficient since the low temperatures south of the Huaihe are not as long-lasting (Xiaojie, 2013).
The need for a sustainable and efficient solution is great if the heating and cooling demand are to be met without dramatic increases in energy utilization.

District heating in the southern regions of China has been impossible earlier with the economic state of the government. Additionally the energy usage is still an issue for the Chinese government, which still provides free and unlimited heating to a fraction of buildings in the north (Almond et al., 2009).

It can be assumed that this has resulted in an unwillingness to pursue district heating solutions (particularly in the south), though official reports are hard to find on the subject.

A district heating solution can, therefore, prove hard to implement. A smaller central heating system on a local scale for a set of commercial buildings is however seen as a possibility. The Chinese policy will guide the solution that later on is proposed.

### 3.1.2 Reducing Carbon Impact using Sustainable Heat Sources

That China is one of the biggest energy consumers in the world is already well known. It’s also the largest emitter of carbon dioxide (Chen and Wang, 2013). Of the country’s energy usage, buildings represents over 30% of the energy usage (Ruhang and Yunna, 2012) and reducing this seems a vital step for a sustainable future. In 2010, 75% of China’s electricity production came from coal (Mathews, 2013). One kWh of electricity from coal emits about 1 kg of carbon dioxide (IEA, 2010), and the total amount of electricity produced in China in 2010 was almost 4 billion TWh (Mathews, 2013). If the electricity produced from coal in China could be reduced by the use of heat pumps a lot of environmental improvements are gained. Not all electricity is produced by coal; oil has about the same emissions from produced kWh electricity, and natural gas has about half (0.5 kg per kWh) (IEA, 2010). Nevertheless, efficiency gains that are made can reduce the electricity demand, simultaneously reducing CO₂ emission.

Zhang et al., 2013, also show that the amount of coal used for production of energy has increased over the last two decades. Using heat pumps with high performance instead of heating with the combustion of fossil fuels could therefore, also reduce the carbon impact (Chen and Wang, 2013). According to Chen and Wang, the carbon dioxide emission from urban district heating which has coal as its main source grows annually by ten percent, and is as of now responsible for 4.4% of the total emissions in China. If the heat could be produced by means of cleaner technology, the emissions will be reduced.

### 3.2 Introduction to Technology

#### 3.2.1 Heat Pumps

Heat pumps are a technique for transferring heat between two or more places. A heat pump cycle is, in its standard form, fully reversible and can be used for heating purposes as well as for cooling. The heat pump is the dominant technology behind the common refrigerator in a standard kitchen. Below follows a description of the standard heat pump cycle.

An evaporator and a condenser are connected by pipes (both are heat exchangers of different sorts). Between them is a compressor that increases the pressure in the system and keeps the fluid circulating. There is also an expansion valve between the condenser and evaporator that upholds the pressure difference (See Fig. 3).
The cycle utilizes a refrigerant (e.g. R134A, CO₂, R22), which alternates between being evaporated and condensed. The condenser and evaporator are both heat exchanger coils that exchange heat with the surrounding environment. In a heat pump cycle, heat is taken from the outside environment through the use of low pressure in the evaporation coil. With a low pressure, even cold outside conditions can evaporate the refrigerant (Natural Resources Canada, 2009).

As the refrigerant passes through the compressor, its pressure increases leading to an increase in the condensation temperature. Compressing the refrigerant raises its temperature, thus creating a temperature gradient between the refrigerant and the heat sink. A small temperature increase is preferable since the energy required is less. Thus, a heat source with stable temperature throughout the whole working season is beneficial (Bohdanowicz and Jonsson, 2005).

The temperature gradient between the refrigerant and the heat sink allows for condensation when passing through the heat exchanger coil on the inside of the building. The condensation is due to the heat from the refrigerant passing to the surrounding, and colder, environment inside the building. Lastly the refrigerant passes through an expansion valve. By restricting the flow of refrigerant, it withholds the temperature and pressure differences. (Natural Resources Canada, 2009).

![Figure 3 - Heat pump/refrigeration cycle. An evaporator and a condenser are connected by pipes (both are heat exchangers of different sorts). Between them is a compressor that increases the pressure in the system and keeps the fluid circulating. There is also an expansion valve between the condenser and evaporator that upholds the pressure difference (Oregon State University, 2008).](image-url)

The same cycle is used for cooling in which case the compressor works backwards and the inside and outside coils shift function.
3.2.2 District Heating

District heating is a way of centralizing the heat production of a region. The benefits of this are many. District heating emits less carbon dioxide, per kilowatt of heat, than a set of local burners. The heating plant can incinerate waste, use waste heat from industry and utilize alternative energy sources that are too problematic to be exploited for any other purpose (Nyström et al., 2009). This solution has the ability to utilize any biogas generated in Wuxi Eco-City as input fuel.

Using oil, waste, biogas or other non-conventional fuels, water is heated at the plant then distributed through a pipe network. The temperatures are season dependent (in Sweden between 70 – 120 °C). The warm water is transported under high pressure to the buildings’ own unit which further distributes the heat. The water then circulates back to the district heating plant. On the way, residual heat can be used to heat sidewalks and prevent frosting (Svensk fjärrvärme, 2013).

The implementation can be expensive. In Sweden laying the pipe grid can cost between 2000 and 12000 SEK per meter (roughly 300-1900 USD, exchange rate at 01-05-2013). The lifespan of the grid can, however, be up to 100 years (Svensk fjärrvärme, 2013). The heating/cooling demand must thus be high enough to motivate the construction of the infrastructure that a centralized system requires (Madani, 2013). The network is a large cost-driver for the district heating system.

3.2.3 District Cooling

District cooling follows the same principle as district heating but the processes for cooling are diverse and tailored to the specific conditions of the region. The district heating and district cooling systems are often used in combination to take advantage of different synergies, but are distributed in separate systems. Techniques that are possible are the use of snow, deep-water lakes and/or seas. When cooling the water a low pressure is used to ensure evaporation at low temperatures (Swedish District Heating Association, 2013).

Finland Fortum has developed a district cooling solution in Stockholm that utilizes an underground storage tank for cooled water. The tank water is cooled during the night, when the demand for cooling and cost of electricity are low. When the demand of cooling is high, during the afternoons, water is distributed throughout the district cooling net (Fortum, 2011-a).

There exist technologies for cheap cooling, known as free cooling. The concept involves circulating already cold water from deep lakes or seas (Energimyndigheten, 2012).

Lake Taihu, which lies in close proximity to Wuxi, is not optimal for the use of district cooling because of its maximum depth of only 3 meters. For district cooling to best utilize a lake, the lake has to be deep. This is because during the summer when the cooling demand exists, a shallow lake will become heated fast. Deep water, however, remain cooled throughout a longer period. The North of Lake Taihu (where Wuxi is located) reaches average water temperatures of 30-32°C during the summer (Qin, 2008), making it unsuitable as a district cooling source.

3.2.4 Solar Thermal Heating

Solar thermal heating harnesses the solar radiation and stores it in mediums such as refrigerants, air or other fluids (Kalogirou et al., 2004). This technique is popular in certain areas for heating domestic hot water. For higher efficiencies the collectors can be combined with heat pumps in an effort to create dual source or solar source heat pumps, which have higher efficiency.
The effect that can be exploited from a solar thermal system depends largely on the amount of solar radiation that the area is exposed to. This can vary both by season and region.

![A close-coupled solar water heater. It heats water for use in DHW supply for the main part. It can be used in combination with a boiler to be used for space heating (University of Strathclyde, n.d).](image)

The solar thermal energy is usually in need of auxiliary heating, to get the right temperatures. This is typically a boiler of some sort, which requires combustion (EcoHeat Solutions, 2009). As such this solution will not be discussed further. A boiler is not in line with the eco city ambition. Solar thermal collectors can however be combined with heat pumps in order to improve the performance. In this case it would be used as the evaporator in the heat pump cycle or as a complement to the original heat source.

### 3.2.5 Heat Sources

A heat source is where the low temperature is taken. The medium or space that the high temperature is delivered to is referred to as the heat sink (Bohdanowicz and Jonsson, 2005). A heat source can be used as a heat sink if the body temperature is lower than the desired feeding temperature.

These sources can either be the surrounding air, a body of water, the ground, the foot of a mountain or the exhaust heat from industry. It is desirable to have a heat source that supplies the same temperature regardless of season and cannot be changed by the system during use. When the source remains unaffected by the system exploiting it and during the shifting of seasons, the source is referred to as a thermal reservoir (Encyclopedia Britannica, 2013) and represents the ideal heat source.
3.2.5.1 Air source

Air source refers to the heat being taken from the surrounding air. Even air at -15°C can be used for this purpose. The heat pump does not affect the surrounding air temperature; the air is constantly renewed naturally (Energy Saving Trust, 2013).

What can affect the performance is the seasonal temperature variation of the surrounding air, which provides the evaporation temperature. With the seasonal variation in temperature, the heating capacity is at its lowest at the same time as the heating demand is at its highest (Bohdanowicz and Jonsson, 2005). If the temperature of the outdoor coil (the evaporator) falls below the air dew point and freezing point for water, then frost will start to gather on the coil (Dong et al., 2012). A remedy to the frost build up on the outside coil is to reverse the cycle using the inside air as a heat source for defrosting (Dong et al., 2012). When temperatures drop below 0°C make-up heating can be needed as a way to compensate for the inefficiency (Swedish Energy Agency, 2011).

The air source is proportionately easy to install, compared to ground source (Energy Saving Trust, n.d.).

Figure 5 - Air source heat pump cycle. An air source heat pump can utilize fans by the indoor and outdoor coils, increasing the airflow across the coils and dispersing the cooled/heated air (Sustainable Homes, 2011).

3.2.5.2 Exhaust Air Heating

An exhaust air heat pump requires that the building is outfitted with a ventilation system of some sort, as the heat is drawn from hot exhaust air that is ventilated out of the building. For full efficiency it requires that the evacuation be centralized to one outlet. In residential buildings the exhaust air can be extracted if the house has centralized ventilation. Most residential buildings also produce warm exhaust air from the use of hot water in the bathroom, or from cooking in
the kitchen, further increasing the amount of heat available (Swedish Energy Agency). The warmth of the exhaust air is utilized before it exits the building at a lower temperature (See Fig. 6).

![Exhaust air to outside](image)

**Figure 6 - Simple exhaust air to water heat pump. The picture depicts exhaust air that exchanges heat with the cold water from the bottom of the tank. The cold water is heated and returned to the tank, while the exhaust air exits the building at a lower temperature (Heat Pump Supplier, n.d.).**

The amount of heat that can be drawn from the exhaust air is largely dependent on the exhaust air flow rate. This is limited in a normal residential house and must be checked before the installation of a heat pump. It’s possible that a heat pump of this sort could produce enough heat to cover the demand of a well insulated house, as long as the ambient temperature stays above about +5°C (Bohdanowicz and Jonsson, 2005).

According to Bohdanowicz and Jonsson the amount of heat that can be gathered from the exhaust air is estimated by:

\[ Q = \dot{V} \cdot \rho \cdot \Delta h \]

The above equation shows the retrievable heat as a function of the volume flow, density and enthalpy difference of the exhaust air.

Moreover, water will condensate on the heat exchanger due to humidity and this has to be taken into consideration as it will involve an additional heat exchange. There is also a chance that frost can be formed on the exchanger if the air is cooled to temperatures lower than 0°C (Bohdanowicz and Jonsson, 2005).

The exhaust air can also be used for heating without a heat pump. This is achieved by heat exchanging the cooler supplied air with the warmer exhaust air. The air streams move in and out of the building through different ducts with the aid of fans. Another name for this solution is FTX system (Energimyndigheten, 2011) and has similarities to waste heat extraction presented in the next section.
3.2.5.3 Waste heat extraction from industry

In many industries heat is created as a side effect of the primary process. Chemical plants, pulp and paper industries and treatment plants are examples of industries where waste heat is produced and removed in either air or water. Collecting this provides possibilities of saving energy by heat recovery. There are five factors that affect the benefits of this heat recovery: power, energy, quality (temperature and purity), time, and place (Bohdanowicz and Jonsson, 2005). This means for example that sufficient heat must be extractable and that it can be done in a nearby proximity to the end-user. Many times it is most beneficial to close the process internally to recover the waste heat and use it in the main process. See figure 7 for a simple schematic over a waste heat recovery process.

Hammarbyverket in Stockholm is an example of how waste heat can be absorbed and used for heating of residential and commercial buildings, but also how it can be used as an internal heat source. The plant collects the heat from cleansed sewage water coming from a nearby treatment plant and distributes it to the heating network in southern Stockholm (Fortum, 2013).

![Simple schematic over a waste heat extraction unit.](image)

**Figure 7** - Simple schematic over a waste heat extraction unit. *The water is heated at the exhaust coil in contact with the waste heat source, and transferred to a supply coil, admitting heat (Building Green 2010).*

3.2.5.4 Water source

The heat is taken from a certain body of water. Water generally has a higher heat transfer coefficient than ground source (Kensa heat pumps, n.d.). One must consider the quality, depth and volume of the body of water to assess the viability of a water source heat pump (U.S. Department of Energy, 2012-a).

The two configurations in which one can exploit bodies of water as heat sources are open loop and closed loop systems.
In open loop systems, the water enters the system from the body of water, passes through the system, and is discharged into the body of water. This is only effective when the water that passes through the system is relatively clean. Potential issues are corrosion, filtration and freezing (Kensa heat pumps, n.d.), thus the quality of the water is of special importance.

A closed loop utilizes the same water, or antifreeze, perpetually and is a closed system. The benefits of a closed loop, as compared to an open loop, are reduced risk of freezing in the heat pump and reduced maintenance costs. The closed loop requires no filtration or other water treatment. It does on the other hand require a small investment in a so-called pond mat, which is a submerged heat exchanger (Kensa heat pumps, 2009).

Water source heat pumps are an expensive technology if the distance to the source body is far from the building, as the costs of well-insulated pipes are high (Berglund, 2013).

### 3.2.5.5 Ground Source

Ground source heat pumps can be built in two different configurations.

The first option is to have horizontal pipes located 0.7 – 1.5 meters under the surface. Preferably the pipes should be placed in wet clay soil with a distance between them of 1.5 meters (Energimyndigheten, 2011. Bohdanowicz and Jonsson, 2005). For every 1 kW of capacity approximately 35-55 meters of pipe are required (Madani, 2013). This then requires that around 500 m² of land is available. The tubes can be configured using a secondary circuit serving as an intermediary between the ground circuit and the heat sink. The other option is direct expansion (DX) with no secondary circuit, results in a better COP since no extra heat exchange process occurs (Bohdanowicz and Jonsson, 2005).

During the winter ice will form around the pipes due to the moisture on the pipes formed by the heat exchange process. For maximum performance it is required that the ice melts during the warmer periods of the year. During the warmer periods it’s also possible to reverse the process and use the ground source for cooling (Bohdanowicz and Jonsson, 2005).

The second option is vertical pipes extending in boreholes around 100-200 m below the surface using rock as the heat source. For one borehole it’s possible to extract about 20 W/m. Just like with the horizontal pipes the ground is warmed up during the late summer and autumn and cooled down during the winter and early spring, making it possible to use the ground as a cooling source during the warmer periods (See Fig. 8). For several boreholes, some sort of recharging aid is required to restore the ground during the warmer periods. This can be achieved through a heat exchange between the air and ground when the air temperature is higher than the ground temperature, giving the possibility to supply cooling (Bohdanowicz and Jonsson, 2005). Vertical ground source heating has a rather high initial cost but low operating costs (Madani, 2013). An issue that vertical drilling face is what types of soil the drilling is commenced in. The pipe has to be connected to the ground, and if the soil consists of sand this is difficult. Moreover, in Sweden it’s recommended to keep a distance of 20 meters between each borehole to maintain a high efficiency of every borehole (Berglund, 2013).
According to Chen et al. (2010) one of the problems that have occurred when installing ground source heat pumps has been an unbalanced heat flow in the ground. This has lead to decreasing efficiency over time. If you only withdraw heat from the ground without allowing the ground to recover, it will eventually reach so low temperatures that the heating possibilities become low. The best locations for ground coupled heat pumps is where the heat withdrawn is similar to heat given to the ground. However, by adding a supplement, GCHPs become applicable in more areas. Wuxi is located within an area that typically has a similar cooling and heating demand, and seems to be within the acceptable region (Chen et al., 2010). It is thus essential to balance the heat flow of the system.

3.3 **Case studies**

### 3.3.1 District Heating & Cooling

The district heating system of Stockholm covered the main parts of the city core in the 1980’s. The system is mutual with several actors that provide it with heat. Only a small part of the system is used for cooling, given the Swedish climate. The demand of cooling usually comes from offices or supermarkets, and is expected to increase (Regionplane- och trafikkontoret, 2008). The small fraction of cooling that is produced is basically a rest product from the heating production (Cederquist, 2013) and is distributed through three connected systems. Even though the main demand in Wuxi is cooling it’s interesting to have a look at the Swedish district heating system to see if there is anything that can be learned from it when considering a possible implementation of district cooling/heating in Wuxi Eco-City. When assessing the feasibility for cooling using heat pumps, this should be compared to the usage of district heating.

There are five major actors that supply heat to Stockholm and manage the net, which consists of four separate larger systems (Northwestern, Southern, Central and Southeastern) and many smaller, separate standalone systems that supply suburbs. The Southern and Central systems are connected since 2007 and this provides the opportunity for actors to cooperate and distribute heat amongst them depending on demand. However, research shows that there wouldn’t be any substantial benefits in connecting more of the nets due to the losses that occur when transferring...
the heat. The total heat produced in the four systems over a year is roughly 12 TWh (Regionalplane och trafikkontoret, 2008). The primary energy sources are bio fuel, waste, coal, and oil where bio fuel and waste represent a fraction of about 0.5-0.6.

The largest five heating plants represent about 70% of the heat produced in Stockholm and all but one of these have a production of more than 1 TWh (Regionalplane och trafikkontoret, 2008). Two of them are combined heating and power plants. Moreover, the construction of one additional CHP plant has just commenced within the Central district heating system. It is dimensioned to produce 1.7 TWh of heat and 0.75 TWh of electricity annually and is expected to be finished in 2016 (Regionalplane och trafikkontoret, 2008).

One of the plants, Hammarbyverket is located close to Hammarby Sjöstad, one of the inspirations for Wuxi Eco-City. The plant produces roughly 1.5 TWh of heat annually using mostly heat extraction from wastewater produced at a nearby sewage treatment plant in Henriksdal. This sewage treatment plant in Henriksdal is connected to more than 700'000 users and around 250'000 m³ of water is circulated every day. The heat extraction takes place in the world’s largest existing heat pump and the exit water supplies the district cooling system, making it an energy efficient system (Regionalplane och trafikkontoret, 2008). This power plant has a measured COP₁ of 3.47 (Fortum, 2011-b).

The district heating in Stockholm also shows great potential to be combined even further with power generation, at the same time reducing carbon dioxide emissions by significant amounts (Danestig et al., 2007).

Another heat source in Stockholm is waste incineration that occurs at Högdalenverket, located within the Southern district heating system. The plant produces around 1.8 TWh of heat and 0.3 TWh of electricity annually (Djuric Ilic et al., 2009). A study was made examining the effects of an increase in waste incineration for district heating and it was found that it would be possible to expand the current district heating system of Stockholm because of lower cost for waste. This would in turn make it possible to reduce the usage of fossil fuels to a larger extent than it would otherwise (Sahlin et al., 2004). However, since the study isn’t entirely up-to-date it’s uncertain whether the same feasibility still applies.

In Xiangtan, south China, a district heating/cooling system was built composed of 14 open-loop water source heat pumps. The system of 14 heat pumps has a common source in the Mengze Lake. Compared to the standard air source heat pump prevalent in south China, the COP value was 0.7-0.85 higher in cooling mode and 0.46 higher in heating mode compared to the same source/sink temperatures. The COP₁ and COP₂ were both around 4 for the entire system. Individually the water source heat pumps had an average COP₁ of around 4.2 and COP₂ of around 4.5. The inlet is placed at 2m depth of the lake, which has a 3m average depth. Water quality is important in open-loop systems. The Xiangtan plant uses non-chemical filters that remove particulates and algae from the inlet water. The pumps will shut down if the inlet temperature has decreased a minimum value which puts the risk of ice entering the pumps.

The peak cooling and heating demands are 12196 kW and 6953 kW respectively. What population size this corresponded to was not reported by Chen et al., it can however be assumed to be less than 20 000 which was the prospected population size of Wuxi Eco-City. The plant could cover the entire demand except on the particularly cold days during the winter, in which
case auxiliary heating is required. The payback of the system was calculated to 5.6 years (Chen et al., 2006).

### 3.3.2 Air Source Heat Pumps

ASHPs are mature technology whose use is widespread around the world. They are particularly prevalent in the south of China (Chen et al., 2006).

Two identical air to air ASHPs were installed at a medical facility of 60 m² in Le Cannet, south France, in 2010. The climate is warm and cooling dominated. The medical facility is located in the flat of a multifamily apartment complex. The SPF of the two heat pumps was 3.77 during the heating season, the average winter temperatures of the region lie around 10°C. The cooling performance wasn’t measured but has a nominal value in COP of 3.21 (Ground-Med, 2011a).

A study performed by Kelly and Cockroft at the University of Strathclyde, Glasgow, analyzed the performance of an air to water ASHP with a nominal COP₁ of 3 and a rated thermal output of 8 kW for heating. The field tests included 10 residential houses, of similar size, in the region of Westfield. The performance data was collected from 8 of these houses since two withdrew from the study. The data showed that the average annual COP₁ of the system was 2.7 (Kelly and Cockroft, 2011).

In Rogny-Les-Sept-Écluses, France an air to air ASHP was studied in 2011. The object was a 90 m² villa that demanded both heating and cooling. In this particular case however, the heat pump didn’t operate in cooling mode because of a cold summer. When only operating in heating mode, the SPF₁ averaged at 3.3 even though temperatures averaged as low as -7°C in February. It was able to meet the heating demand without using any backup heater with a reported heating capacity of 6 kW (Ground-Med, 2011b, Sepemo, 2011).

In Newcastle, England 85 connected apartments are heated by nine air source heat pumps of 28 kW each. It was completed in 2009 and the constructor stated that it was more cost-effective than using the ground or the nearby river Tyne as the heat source (Dimplex, 2011).

### 3.3.3 Variable Refrigerant Volume in Shanghai

The institute of Refrigeration and Cryogenics at Shanghai Jiaotong University have performed an experimental analysis of the Variable Refrigerant Volume (VRV) system, preceded by a simulation, for Chinese conditions. The system is tested in Shanghai; it can be assumed that the local parameters for Shanghai coincide with the parameters for Wuxi, since the cities are circa 128 km apart (Oberheitmann et al., 2012). The study, performed by Zhou et al., simulated and tested the COP of a VRV system during the month of August, when the cooling load is significant. Data concerning the climate, thermal properties of the building and humidity were collected in order to create a realistic simulation. Heaters and humidifiers were dispersed throughout the building to simulate the heat produced by the human occupants during office hours.

The COP is shown to be lowest in the mornings, when the system works with full-load, and then improves during the day when it is working at part-load (Zhou et al., 2008).

The system is energy efficient, flexible, easy to maintain and has good thermal comfort (Xiangguo et al., 2013). It can be integrated with the ventilation system, known as a HVAC system (Zhou et al., 2008), which can be an economical solution for the commercial buildings.

The COP₂ of a common heat pump tends to lie around 3 given ideal conditions (Bohdanowicz and Jonsson, 2005). The VRV system has a daily average COP₂ that varies between 4 and 5.
A high COP\textsubscript{2} value implies good energy efficiency, which translates into energy savings and cost reductions. The experiment was performed in August and as a cooling cycle. When used for heating purposes in winter the COP\textsubscript{1} will likely be higher (since theoretically COP\textsubscript{1} = COP\textsubscript{2} + 1) and the costs likely reduced further, partially due to the milder load in winter.

The system is similar to a split type air conditioning unit, which refers to that the condenser and evaporator coils are separated into out-door and in-door units (Ecoair, n.d.). The VRV system has a set of in-door units. The outdoor coil and variable heat pump regulate the amount of refrigeration or heating that is circulated to the system of strategically placed air conditioning units (Zhou et al., 2008). The system can be controlled through different algorithms and can be regulated locally, which makes the system flexible.

The system is built up of individual units that are coupled to the central out-door unit. Repairs and maintenance are therefore simpler to perform without disturbing the rest of the system.

A study performed by Xiangguo et al., centered on the capacity control algorithm, produced results for new algorithms that decrease the capital cost of the implementation by means of simplification. The new algorithm also provided smaller fluctuations in temperature leading to greater thermal comfort (Xiangguo et al., 2013).

### 3.3.4 Ground Source Heat Pumps for Heating and Cooling

In Wuxi there is as earlier known, both a heating and cooling demand because of the climate. GSHP has been well implemented in colder areas of the earth, where heating is the main concern (EGSHPA, 2011). However, when heating something you always withdraw the heat from somewhere, giving the opportunity to also utilize a heating system for cooling (EGSHPA, 2011). This is done for example in Hammarby Sjöstad, Stockholm, where the cooling for office spaces and such is a byproduct of the heat that is withdrawn from used sewage water (Cederquist, 2013).

Not every GSHP system utilizes the byproduct (heat or cold) though, but because of the climate in Wuxi where both is demanded we will only look into such cases where both heating and cooling has been provided using the same system. Also, because of the urban area that Wuxi Eco-City is going to be we don’t consider case studies of the horizontal GSHP because of the large area they require.

Ground-Med is an institute that looks into implementations of GSHPs in Mediterranean climate, which is similar to the climate in Wuxi with hot summers and medium to cold winters. They have collected several case studies that are interesting for this study.

#### Small Buildings

In Ramallah, Palestine a geothermal heating and cooling system was implemented in a 300m\textsuperscript{2} villa. It’s COP\textsubscript{1} was measured to be 4.4 at a certain time. It utilizes ten boreholes of 70 meters with a ground heat-exchanger. The building had before installation a cooling load of 23 kW and heating load of 21 kW. Before the implementation the villa was insulated to meet EU insulation standards, which we also can assume the buildings in Wuxi Eco-City meet. Compared to the diesel-powered boilers for heating and forced-air system for cooling, this GSHP reduced the yearly energy usage by about 32000 kWh (Al Sabawi & Green, 2008). The COP\textsubscript{1} obtained in the case study will be considered as an SPF value, because it’s been measured and the ground temperatures can be approximated as being constant (Madani, 2013).

In Keratea, Greece an office building of 150m\textsuperscript{2} is heated and cooled using a geothermal heat pump consisting of five boreholes of 25m. It’s a two loop system with a water-to-water heat pump.
exchanger. The heating and cooling is distributed through four fan coils in the building that operate at 40°C for heating and 7°C for cooling. The GSHP was designed for a COP of 4, but the measured average SPF was only 2.49. It had an energy input of about 5000 kWh and output of about 12000 kWh (Ground-Med, 2005a).

In Setúbal, Portugal two GSHPs with capacity of 15 kW each are used for cooling and heating of 220 m² at a university. They use five 80 meter boreholes. The space requires a yearly heating of 10560 kWh and a yearly cooling of 7040 kWh. The heat pumps have a capacity of 15.8 kW for heating and 11.4 kW for cooling. The SPF hasn't been verified but the COP, has been measured to be above 5.5 and the cooling EER was measured to be 15.35 which translates to a COP of around 4.5 (Coelho et al., 2007).

Near Bologna, Italy a 150 m² villa is heated and cooled using a geothermal heat pump that utilizes two boreholes of 80m. The hot water is supplied with a solar panel on the roof with a back-up condensing boiler. The boiler is used to support the hot water heating during the winter, and can also be used to support heating in the house, but it was never necessary during the measuring. The boreholes were designed to withdraw 40 W/m (based on the soil), resulting in 1800 kWh of heating/cooling delivery. In reality, the measured input was higher than, circa 2500 kWh. The COP for heating and cooling was designed to be 5.18, high-end performance, but was never measured (Tinti, 2007). This will carry less weight since the performance was never verified with measured data.

**Larger Buildings and Complexes**

Pujiang Intelligence Valley is an environmentally friendly district that was built in Shanghai. It's about 700,000m² in area and implements both solar and geothermal heating technologies. The first offices in the area operated on 75 percent less energy than the normal office in Shanghai. This was, in part, attributed to that the heat pump only has to operate one in three days and still provide the sufficient heating (Cherry, 2007). The buildings are heated during the winter and cooled during the summer using a 100 m long underground geothermal heat pump, which keeps the temperature between 18-26°C depending on the time of the year. The soil temperature is unchanged between 16-18°C at the depth of the heat pump; therefore it's suitable for both heating and cooling (Pujiang Intelligence Valley, n.d., a). For the heating of water used for cleaning and cooking, solar energy is utilized using panels on the roof. No specific COP values were measured, though accounts from the workers attest to the improved comfort (Cherry, 2007).

In Athens, Greece a solar assisted ground source heat pump (SAGSHP) is utilized to provide heating and cooling for a 3000 m² building complex. It uses solar water heaters to provide hot water to the building, and also solar air collectors to pre-heat air during the winter. The ground source is water, but it’s in an autonomous loop, thus not open-loop. Two heat pumps are used to supply 170 kW of heating and cooling. The measurements of the system showed that a bit over 60% of the buildings energy usage was covered by geothermal heat source and 20% was covered by solar energy. The measured COPs of the heat pumps were 3.91 and 4.3 respectively (Karagiorgas et al., 2004).

In Louisiana, where the cooling demand is higher than heating demand, 4000 geothermal heat pumps were installed in an army base with approximately 23,000 habitants. The system consisted of 6,600 closed loop GSHPs using 8000 boreholes of 40-100m. Compared to the system before which to 80% used air-source heat pumps and electric water heaters, the system now save 23.3
million kWh of energy annually. The system provides both cooling in the summer, heating during the winter, and hot water generation using so called desuperheaters (IGSHPA, 1996). A desuperheater is an extra heat exchanger that utilizes the superheated gases being produced in the heat pump compressor to heat water (DoE, 2012-b). Although the system isn’t state-of-the-art it shows that implementations of heat pumps are feasible on a grander scale.

In Nashville, Tennessee a GSHP system was implemented in a university building of 7000m². It consists of 144 boreholes drilled to a depth of almost 100m, about 7m apart, and is expected to save 50 to 75 percent of traditional heating costs (IGSHPA, 2006). In Austin, Texas several elementary schools implemented geothermal heating in the early 90’s with energy savings of 25% (Geothermal Heat Pump Consortium, 1997). An earlier composed before-and-after comparison of these schools showed that the electricity demand was clearly lower after the installations of the GSHPs (Cadwaller, 1994).

In the Sichuan province in China located at about the same latitude as Wuxi a vertical ground coupled heat pump is used to supply heating and cooling to an apartment complex of 38000 m². In total, 220 boreholes were drilled to a depth of 65-80 meters. Using billing systems that was installed in each apartment the COP for the whole system was calculated and averaged 3.63 in the summer and 3.49 in the winter. For the heat pumps in themselves, the COP was measured to be 4.68 and 4.42 respectively. During the summer when the soil is used as a heat sink and the outside temperature is warmer, the underground temperature went up to a maximum of 5°C above the undisturbed temperature. In the winter it went down to a maximum of 4°C below the undisturbed temperature. This indicates that a ground coupled heat system must be run for both heating and cooling (Li et al., 2012). In turn, this indicates that these systems are most suitable in environments with warm summers and medium to cold winters.

In Massachusetts, U.S.A, two boreholes of 475 m each utilize groundwater to provide both heating and cooling in a public library building. The system is designed to provide indoor temperature of 21 degrees year round and it does this by holding a SPF of 3.5 (Heat Pump Centre, 2002b). The system was built in 1995 and cannot be considered a modern system in that regard, but compared to the heating and cooling system beforehand it reduced energy demand by almost five times.

In Lyon, southern France a five-story office building of 16633 m² is heated and cooled using a groundwater-source heat pump (water-to-water). The total capacity of the system is 1200 kW and is capable of providing both heating and cooling simultaneously, providing opportunities for increased comfort. The average outdoor temperature during the summer is 32°C and during the winter -8°C. This is similar to the Wuxi climate. The indoor temperature is throughout the year maintained between 19-27 degrees, showing an “acceptable range” principle which should be applied in the modeling of the Wuxi heating system. The COP of the system was stated to be 4.75 for heating and 3.75 for cooling from measurements taken under test conditions. The system was also compared to two other systems using gas-fired boilers and it was shown to have three times less CO₂ emissions than those (Heat Pump Centre, 2002).

A bivalent, two geothermal heat pump system with groundwater as a source is used for cooling and heating of a hotel situated in Greece, with a building area of 8980 m². The system is open loop with two wells at the depth of 60 m for the supply of 17°C water that is used either as a heat source or a heat sink, depending on if the heat pump is in cooling mode or heating mode. The efficiency is increased by heat exchangers that, using the heated/cooled water exiting the building, exchange heat with the inlet water (a FTX system using water). The building can thus be
regarded as a heat source/sink depending on mode. Finally, the water exits the system through so-called re-injection wells separated from the supplying wells. The system provides 7°C water for cooling and 40°C water for heating and has a SPF of 4.54 for heating and 3.65 for cooling. As a side-note, the system was shown to have a pay-back time of less than 5 years (Karytsas & Paskalis, 2008). The SPF for cooling was referred to as SEER in the case, which must be a mistake by the author. Thus this value will be interpreted as a value for SPF₂, since a SEER of 3.65 would otherwise correspond to a COP₂ of about 1.

3.3.5 Solar Assisted Heat Pumps

A so-called Solar Assisted Heat Pump (SAHP) is a heat pump in which the evaporation process of the refrigerant is assisted by solar energy and ambient air (Li et al., 2007). The technique is more than 50 years old (Chow et al., 2012) and has been subject to many analyses of performance. SAHPs seem to be most viable in the sunny belts of the Earth, which for example contains Turkey (Hepbasli & Ozgener, 2007). Wuxi’s latitude position is approximately within the same latitude as Turkey. Moreover, another experiment concludes that the installation of a thermal storage tank is essential when installing any SAHP system (Kuang et al., 2003).

Direct Expansion SAHP

Recently the SAHP technique was tested in Shanghai using two different setups (Dai et al., 2011, Li et al., 2007). In these experiments the heat pumps were both of a direct expansion (DX) technique, where the refrigerant is in direct contact with the source of heating or cooling. This eliminates the need of a pump for circulation on the source side, and thus there are less heat transfer losses that would occur during that circulation (Ochsner, 2008). The first test used a multi-functional DX-SAHP with a surface collector area exposed to the sun of 10.5 m². It could be altered to do either water heating, space heating, or space cooling. During the water and space heating experiments it was shown that the heat pump was viable for use, having a COP between 2.1 to 3.3 for space heating and able to heat 200 liters of water a day to 50°C if used for water heating. When used for space cooling however, it was shown that it couldn’t suffice for a whole days demand (Dai et al., 2011).

The other test used a DX-SAHP Water Heater with a collector area of 4.2 m². In this experiment the heat pump was able to heat 150 liters of water from 13.4 to 50°C with a COP varying between 3.11 and 6.61 depending on conditions.

In the PIV-park in Shanghai, solar energy is used for the heating of water that is later used throughout the office building complex (Pujiang Intelligence Valley, n.d., b)

SAHP for Space Heating

An experiment was made during the heating season in northern China using a SAHP with water source for space heating (Kuang et al., 2003). The ambient air was between -10°C and -4°C, which is a little colder than in the Wuxi winter season. The COP measured in the experiment averaged at 2.19 and could meet the heating load even during the coldest days. It used surface collectors with an area of 11 m².

The author concluded that an auxiliary heater is necessary when using SAHP systems for space heating, the extent to which this is true for the Wuxi climate is unclear. As earlier mentioned, the thermal storage tank proved to be an important component to the system in order to handle differences between solar radiation and heating demand.
Cervantes et al. from the National University of Mexico concluded, in an exergy analysis of an SAHP system with air source that the main source of irreversibility was found in the solar collector (Cervantes & Torres-Reyes, 2002). This emphasized that the incoming solar radiation was not fully utilized.

**Growth potential**

Recently, Dai et al. from the Institute of Refrigeration and Cryogenics at the Shanghai Jiaotong University conducted an experiment of a hybrid air-solar CO$_2$ heat pump, comparing it to the ordinary single source equivalent. They found in turn that the heat pump’s energy efficiency increased and the energy savings for a year was around 19.3% (Dai et al., 2011). The heat pump would run the whole year and could reach COP values of 3.8.

For further increases in efficiency a two-stage DX-SAHP can be installed. The principle is that the system is split into two circuits, one with a low pressure compressor circulating the refrigerant between the solar collector and a flash chamber, the other with a high pressure compressor and refrigerant passing through the flash chamber into a heat exchanger (See Fig. 9). The flash chamber mixes the high-temperature and low-temperature refrigerants of the two circuits and functions as a heat exchanger (Abdel-Salam et al., 2009).

The improvement in performance is derived from the high condensation temperature. The two-stage DX-SAHP has the potential of generating more output for that same input (Abdel-Salam et al., 2009).

![Figure 9 - Schematic of the two-stage direct expansion solar-assisted heat pump system. The two circuits (low pressure and high pressure) connected by a flash chamber working as a heat exchanger (Abdel-Salam et al., 2009).](image)

In Tianjin, China a SAHP was designed and tested during winter time to provide heating for a building in the region. It reported an average confirmed COP of 2.97 with a high of 4.16. The villa was 820 m$^2$ large and the desired indoor temperature was 18 during the winter (Kegel, 2012).

A similar technique is also being tested at The Royal Institute of Technology (KTH) in Stockholm, where solar energy will support an air source heat pump during the wintertime when the outside temperature become too low for the heat pump to operate solely using air source (Ignatowicz, 2013)

**3.3.6 Dual Source Heat Pump**

A joint effort between the University of Nebraska-Lincoln, U.S.A, and Harbin Institute of Technology, China, created a prototype for a multi-functional dual source heat pump. The
The prototype outperformed the unmodified market-available air-source heat pump original (Liu et al., 2013-a).

The heat pump had several modes of working. It had capabilities to perform:

- Space heating
- Space heating and domestic hot water (DHW)
- Space cooling
- Space cooling and DHW

Unfortunately the experiments were only conducted for the heat pump in heating mode (heating + DHW, Heating alone, DHW alone) (Liu et al., 2013-a). Though this study only inspected the heat pump in heat mode, the system can be expected to outperform the unmodified heat pump in cooling as well given the dual source advantage.

The prototype setup included one DHW supply system and a HP system. The HP system included an accumulator, a compressor, an in-door heat exchanger with a fan, an out-door heat exchanger (for air source) with a fan and a gray water tank with a DX coil heat exchanger. The prototype also included several valves that allow switching between the different modes (Liu et al., 2013-a). Gray water refers to the wastewater that comes from domestic activities, including sink water, bath water, laundry water and such. It does not include sewage water.

The setup allowed different configurations of the dual source construction:

- Air-source only
- Gray water-source only
- Gray water and air in parallel
- Gray water and air in series

Since the tests were done in heat mode only, both the out-door air heat exchanger and the Gray water tank with DX coil were used as evaporators in all configurations. The in-door unit became a condenser. The parallel configuration was achieved by adjusting the refrigerant flow to pass through two routes simultaneously and get optimal usage from both sources. The series configuration prioritized the gray water heat source, placing it first, to then route the refrigerant to the air heat exchanger.

The gray water tank was always kept at the minimum volume, 220 gallons (roughly 833 litres), in order to measure the lower bound of the performance for a typical usage. The heat pump rig was tested for outside temperatures of 15.6° C, 8.3° C and 1.1° C, whilst the acceptable in-door temperature was set to 21.1° C plus minus one degree. For the DHW the water temperature was kept at 48.9° C plus minus one degree (Liu et al., 2013-a).

The experiments showed that the performance of the different source configurations varied depending on the outside temperatures and the working mode. For the “space heating alone” mode, the parallel source configuration had the highest COP, when the out-door temperature was 15.6° C. When the temperature dropped to 8.3° C the water source gave the best COP, followed by the parallel system. The parallel system provided however the best heat capacity. When the out-door temperature fell to 1.1° C the parallel source configuration provided the best COP. All configurations performed worse in both heat capacity and COP when the temperatures dropped (Liu et al., 2013-a).
When the system produced both DHW and space heating the COP\textsubscript{1} was better for each respective configuration. Although, the heating capacity was reduced when also heating DHW, the decrease was less than 12\% compared to the respective configuration for the space heating only. The performance of the parallel configuration was the best at 15.6\textdegree C as well as 8.3\textdegree C, in both COP\textsubscript{1} and heat capacity. When the out-door temperature was 1.1\textdegree C the series configuration displayed a slightly higher COP\textsubscript{1}. The experiment concludes that the parallel configuration of the air source and the gray water DX source provides the highest performance and the air source had generally the worst performance (Liu et al., 2013-a).

The COP\textsubscript{1} of the parallel source configuration varied between around 3.25 to around 4.7 depending on the mode and the out-door temperature.

### 3.3.7 Water Source Heat Pumps

Water source heat pumps can utilize many types of water bodies. Lakes, oceans, seas, rivers are amongst the options available. In Savona, Italy, a large oceano-thermal solution with several heat pumps was implemented to cover the heating and cooling need of a large residential/commercial building. The building has a total indoor area of 21 000 m\textsuperscript{2}, 4 000 of which belong to a 96 room hotel (Ground-Med, 2005b).

The seawater is used as a heat source, providing heat in the winter and cooling in the summer. The seawater is pumped in to a central heat exchanger which is connected to a secondary circuit (closed loop) that services each dwelling through its own separate pump. The system was implemented in 2005 and has since then provided cooling during the summers, heating during the winters and hot water throughout both these periods. The COP\textsubscript{1} of the system is 5. The SPF\textsubscript{2} during the heating season for the system was measured to be 4.2 (Ground-Med, 2005b).

Interesting is also the similarity in climate between Savona and Wuxi which makes the technology, in theory, transferable with the same performance.

In another part of Italy, a case study of a water source heat pump was made from May to September. The heat pump is designed to heat and cool an area of 300 m\textsuperscript{2} using the nearby lake as the heat source/sink. The system that uses air to distribute the heat and cool is closed with three separate loops and two heat exchangers. During the five months studied, the COP\textsubscript{2} was measured to be between about 3.6-4.2 with outdoor temperatures at 19-27\textdegree C (Maso, 2006).

The district heating and cooling solution in Xiangtan is also comprised of water source heat pumps. The measured COP\textsubscript{1} averaged around 4.2 and measured COP\textsubscript{2} around 4.5 (Chen et al., 2006). The higher COP\textsubscript{2} might be due to a lower difference between source and sink temperatures during the cooling season.

### 3.4 Market available Heat Pump Solutions

The following section presents known brands in HVAC technology and compares their products within the different categories. Experimental technologies (SAHP and DSHP) were thus not included. A research of the market available heat pumps was made in order to attain further insight into the average performance of the different technologies and the current market situation including the latest models. District heating is not considered because it's not possible to buy standard systems from any manufacturer. Furthermore, solar assisted and multifunctional heat pumps are not considered because they are immature technologies and virtually unavailable.
on the market. Air source and VRV are only considered in market situation analyses, not for performance evaluations since they're dependant on local climate conditions.

Performance data from manufacturers can vary because COP is measured according to different standards. The standards include different source temperatures, outlet temperatures, and different requirements. The manufacturer COPs are static and usually tested according to only one standard. This means that the COP could have a slightly different meaning from one manufacturer to another (Thermia, 2012). The two most common standards are EN14511 and EN255. EN14511 is usually lower because it also considers the circulation pump in the heat pump. EN14511 uses a feeding temperature of 45°C, whilst EN255 uses 35°C (SP, 2013). The COP measured with regards to EN14511 seems to be about 0.5 points lower on average (Thermia, 2012). This is also the fairer value and better resembles how the heat pump will perform annually. The three largest Swedish heat pump manufacturers IVT, Nibe, and Thermia are fairly consistent in their evaluations and mostly use the same or both standards except in cases where one of the standards is unsuitable.

### 3.4.1 Air Source Heat Pump

Manufacturer information about air source heat pumps is difficult to interpret since their performance change substantially if the surrounding conditions are changed (Madani, 2013). Therefore it’s no use in comparing manufacturer data COP, because they are only measured at a single temperature. However, the market for air sources is mature and many big manufacturers offer a wide range of ASHP products (Fujitsu, 2013, Sanyo, 2013, Daikin, 2013). It is safe to say that there is an air source heat pump available for most climate conditions. Instead, the data received about ASHPs from case studies will, in this report, provide the basis for performance evaluation.

### 3.4.2 VRV system solutions

Since the evaporator of the VRV system utilizes ambient air as its source, it has the same issue with data interpretation as air source heat pumps. However, these systems are being sold by large manufacturers (Fujitsu, Sanyo, Daikin), which increases the legitimacy of the technology.

### 3.4.3 Ground Source Heat Pump

**Nibe:** Nibe has 8 different types of ground source heat pumps utilizing both water and soil as the heat source/sink. Three of these operate in both heating and cooling modes. The largest of these operates in the ranges 8-12 kW and requires boreholes of 140-190 meters (Nibe, 2013).

**Bryant:** Bryant has three different geothermal heat pump models which seem to be high-end. They provide both heating and cooling. One of the heat pumps accordingly has a COP of 4.7-5.3 and an EER of 29-35. The capacity is about 5-21 kW (Bryant, 2013).

**Thermia:** Thermia have several different geothermal heat pumps that can do heating in the winter and cooling during the summer. The largest model has an effect between 5.8-17.2 kW and COP of 4.5-5 for heating according to EN14511 and 4.2-4.6 according to EN255 (Thermia, 2013-a).

**IVT:** Swedish IVT has three types of GSHPs in the ranges 5.5-17 kW. The premium model is stated to have a COP of 4.8 according to EN14511 (IVT, 2013).
3.4.4 Water Source Heat Pump

*Carrier:* Carrier has four different water source models. One is called 30WG which operates in the ranges 20-90 kW. It has a cooling EER of 4.7 and a COP for heating of 5.7. Their biggest model is the 30XWH which operates in the ranges 252-1752 kW with cooling EER of 3.8-4 and heating COP of 4.8-5 (Carrier AB, 2013-a).

*Thermia:* Thermia have two models that use water as the source. They operate in the ranges 20-42 kW but can be connected in chains. They have a COP of around 3.7 for heating according to EN14511 (Thermia, 2013-b, Thermia, 2013-c).

*Daikin-McQuay:* Daikin-McQuay has several water source heat pumps. One model is operating in between about 3-22 kW and has a COP of around 5.5 and an EER of 16-19 (Daikin-McQuay, 2013).

*Lennox:* Lennox has one large roof-top model that utilizes water as the source. It has ranges between 48-225 for heating or cooling. It has been installed in at least three locations, but no COP is stated (Lennox, 2013).

A significant part of the data collected, through researching the performance of the market available solutions, is unreliable. There is considerable uncertainty concerning the methods and interpretations of the data. The data was presented for rough assessment and to present the market available technologies. Data that is considered unreliable will be removed from the evaluation process.
4 Simulation Methodology

4.1 Simulation Description

The model will create a scenario where an estimate of the energy usage for the residential buildings of Wuxi Eco-City is made.

The model accepts data for the hourly Q values (heating/cooling load in W or kWh). The Q values can be provided for three different building types and are external elements inputted into the system (The model interprets negative Q values as cooling load and positive Q values as heating load). The Q data used in the scenario is retrieved from a study carried out by Engdahl & Wallgren (2013), which investigated the energy use in residential buildings in Wuxi. The buildings were designed to consist of seven floors including basement with a total floor area of 2331 m$^2$, and are corresponding to how the actual buildings in Wuxi Eco-City could look. The difference between the three building types lies in the construction material used for insulation, light reflection and similar benefits. Comfortable indoor temperatures were considered to be 20$^\circ$C during the winter and 24$^\circ$C during the summer (Engdahl & Wallgren, 2013).

Filtered through one of the technologies, the Q value is translated into power rating. The energy usage is perfectly correlated to the Q value. The model assumes the behavior of the heat pump is set to follow the Q value through the use of a thermostat or a person regulating the heat pump manually. The mode of the heat pump should be regulated in such a way that the average power equals the Q value of the hour. A natural assumption since the temperature would otherwise drop below what would be acceptable for the thermostat or comfortable for the inhabitant of the room.

The model accepts the Q data and calculates the energy utilization of each building given a certain heating/cooling solution. Energy usage is thus calculated per building and technology, giving 12 different calculations (3 building types*4 heating/cooling solutions). The total energy usage for the residential district is thus achieved by inputting what amount, and type, of the buildings will use each solution type. In the scenario displayed in this report, a building type ratio of 1:1:1 is used with 60 buildings in total.

The model has an input denoted as “max output” for each building. This represents the dimensioning process for the solution installed. In Sweden it’s recommended to cover 95-97% of the demand (Berglund, 2013), and this is assumed here to be an optimal level in Wuxi as well, in order to maintain a sufficient level of comfort. The reason behind this dimensioning is that the alternative of covering 100% of the demand would lead to unnecessarily large heat pumps and thus a more costly solution. Instead, alternative means of covering the last percentage, such as electrical heating or an extra auxiliary heating is installed (Berglund, 2013). In the scenario this dimensioning principle is used.

The COP performances of the ASHP and the VRV are set to vary with the temperature difference between the indoor and the outdoor climates. The temperature data was achieved from the work by Engdahl & Wallgren (2013) and can be considered as typical weather data for the Wuxi region. The variance, the ideal COPs, and the minimum COPs are adjustable in the model. The variances for the ASHP and VRV system are set to a default of 3% per degree of temperature difference (in Celsius). A minimum is set because the heat pumps generally reach a point of stable performance (Madani, 2013). The COP performances of the GSHP and WSHP are taken as average performances. This is motivated by that the ground has an even temperature
throughout the year and the performance is thus not as variable as for other heat pump solutions. Water has even temperatures at deep levels but not at shallow levels. For simplification, water temperatures are assumed to be even in this report.

The scenario is created using approximated and retrieved data to estimate the energy utilization of the whole residential sector. The model is versatile and adaptable to new data. It can easily be modified to render more scenarios than the one presented in this report.

See Appendix A1-A2 for an overlook of the model.

4.2 Sensitivity analysis

The Sensitivity analysis is performed on the factors that affect the COP of the each of the different technologies. This is in order to measure how the performance varies with variations in the assumptions built into the model. These are considered to be the parameters of interest.

For the results of the sensitivity analysis see Appendix B.
5 Evaluation of Solutions

For the evaluation of the most viable solution for Wuxi Eco-City, each solution was assessed on four parameters; performance, scalability, implementability and risk. Scalability and Implementability will be treated together since the parameters are, to a great extent, alike and interconnected.

5.1 Performance

Performance is the evaluation of how efficient the technology is at converting energy (electricity) into heating/cooling. To investigate the performance, the technologies’ COP₁, COP₂, SPF₁ and SPF₂ were estimated based upon an assessment of the case studies and a critical point of view on the relevance of the data. Where no data was available, no estimation was made.

Values that diverted to a large extent were disregarded. The COPs are ideal values that will be used for simulation purposes. These are higher than the actual SPF values would be. The values for SPF were disregarded if they were designed values without any measurement to confirm them, but COP values weren’t disregarded in this sense.

The result was collected and inserted into a table (See Table 1). The performances of each technique are more thoroughly evaluated in the following sections.

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Table 1 – Estimated SPFs and Ideal COPs. Based upon an assessment of the case studies

5.1.1 District Heating and Cooling – High Performance

Hammarbyverket, the district heating plant built in Hammarby Sjöstad, has a set of 7 heat pumps which together provide heat to the network. This power plant has a COP of 3.47. The power plant uses waste heat extraction as a heat source. The district power plant in Xiangtan, south China, has an overall COP between 4.2 and 3.5, which utilizes lake water from Mengze Lake in the nearby region (Chen et al., 2006). The District Heating/Cooling systems are believed to maintain a heating SPF between 3.4 and 4 and to be of high performance due to the stability of the systems.

5.1.2 Air Source Heat Pump - Medium Performance

ASHPs have a performance that varies over the season. The variance is correlated to the ambient temperature which will vary considerably more than ground or water temperatures. The performance of the ASHP will decrease rapidly with increasing, or decreasing, ambient temperatures leading to low average performance. As an approximation the COP changes about 3% for every degree of temperature difference (Madani, 2013). In regions with periodically cold temperatures, frost can start to accumulate on the evaporator, which is detrimental to the
performance. A new frost free ASHP is proposed by Yongcun et al. at the University of Zheijiang. This system would retain a higher performance, than the traditional ASHP, at lower temperatures. The system is however still in the experimental phase of development (Yongcun et al., 2011). ASHPs are reliable and are believed to be able to maintain a heating SPF around 3.5, which motivates a rating of medium performance.

5.1.3 VRV system - High Performance

The performance of the VRV system is considered to be high due to that the distribution algorithms and the multi-split construction allow for a good control over the internal climate. The COP values of the test case were between 4 and 5 for cooling. Though information is only available for COP₂, an ideal COP₁ for heating has to be estimated for the simulation. The Daikin VRV III-S is stated to have a higher COP value for heating (Daikin, n.d.) and therefore the ideal COP₁ for VRV systems are considered to be 5.5, which is a bit higher than for cooling.

It should be noted that the VRV technology is a system. The performance is thus dependant on the space being heated or cooled, the dispatchment of the different units, and whether high capacity indoor units in fewer quantity or low capacity indoor units in greater numbers are being used. The performance assessment is, therefore, a more complex and more uncertain evaluation than for the other technologies discussed in this report.

5.1.4 Ground Source Heat Pump - High Performance

GSHPs generally have high COP values. The ground temperatures vary less than water and air temperatures allowing for high performance. The values of COP and SPF of the GSHPs seem to lie around 4.6 for heating and 4.2 for cooling, as shown in many of the case studies. COPs that have been measured at a fixed time will be considered to be SPF values because of the stable performance of GSHPs. The SPF could of course, in actuality, become lower than a COP measured during a certain time, due to certain disruptions.

Three values for heating diverted (both higher and lower) from the others which tended to lie around 4.6, which is the estimated SPF₁ value, and were disregarded. One design value and a very low value of 2.49 were also disregarded. The estimated SPF₂ (4.2) is only slightly lower than the estimated SPF₁, because there were cases when the observed values for cooling tended to be as high as for heating. One value for cooling was disregarded because it was only a design value.

The market available GSHPs previously presented are stated to operate with similar values. This gives the GSHPs a high performance rating.

5.1.5 Solar Assisted Heat Pump - Varying Performance

The SAHPs have from the cases studied shown to have a volatile performance. The range, of COP values, stretches from 2.7 to 6.61. To draw a conclusion as to the general performance of a SAHP would be impossible since the differences in design and purpose (of the SAHPs studied here) are too large.

5.1.6 Dual Source Heat Pump - Medium Performance

The Dual Source Heat Pump, presented earlier, has a heating COP that varies between 3.25 and 4.7. The system represents an attempt at utilizing the heat energy of alternative sources that would otherwise leave the system (household or commercial building) and be needlessly discarded. This could be a technology for the future, since using two different sources could give
it increased flexibility. Using the heat from gray water leaving the system, as in the
described case, is a way of increasing the energy end-use efficiency. This concept entails
achieving more per unit energy spent and is quickly deployable as well as inexpensive (Lovins,
2005). Though the concept is known it is not market available yet. It’s given a medium performance
rating due to promising test results.

5.1.7 Water Source Heat Pump - High Performance

WSHPs, as GSHPs, display high COP values. The water temperatures of the sea and lakes vary
less than the ambient temperature. The variance in this case is dependent on the size and depth
of the body of water. Deeper in the water the temperature is more stable increasing efficiency for
the heat pumps. The studied COPs and SPF lies above 4 on average, but don’t seem to differ
between heating and cooling. This motivates a high performance for this technology. In the case of
WSHPs, as well as GSHPs, the thermal performance is tied to the local conditions.

5.2 Scalability & Implementability

Scalability is a parameter that considers the range of sizes the system can be built in. The rating is
based on the construction of the technologies reviewed in this report. The factors that matter for
scalability are the size of the building or complex in which the technology is used, size of the heat
pump system, the total effect of the system, but most importantly the range of these factors for
each technology. For example, if a technology is used within both a small residential building and
a larger office complex at different locations, it’s considered highly scalable. However, it’s not
possible to compare all case studies using all factors, simply because the data is insufficient in
many cases. In those cases it might be necessary to value the scalability from just one factor.

Implementability defines how easy it is to actually implement the system into the area. It takes
into account the necessary requirements in the environment and climate, the cost, amount of
maintenance, and the beforehand planning needed. It’s also denoted from low to high where high
is the best, meaning that it can be implemented almost everywhere.

5.2.1 District Heating and Cooling - Low Scalability & Low
Implementability

Given the large amount of investments, planning and construction a district heating system
requires, the implementability should be considered as low. Furthermore a district solution would
require government decisions and synchronization.

The scalability for this solution type is also low due to the significant investments that the
solution requires. The system is thus in need of a certain size for it to be economically viable.

5.2.2 Air Source Heat Pump - High Scalability & High
Implementability

ASHPs are a mature technology that can be used for both heating and cooling. It is popular
amongst manufacturers, comes in many different sizes and is easy to install (Fujitsu, 2013; Sanyo,
2013; Daikin, 2013). For usage where the demand is higher however, several heat pumps are
required. In larger cases, a VRV system might be preferable because it’s more optimized for use
in large buildings. ASHPs can operate down to temperatures of -15° C, so it’s not suitable where
the climate is too cold but this is not the case for Wuxi. In cold and humid climate there is the
risk that frost will form on the coil, which reduces the efficiency of the heat pump, eventually
leading to the need to defrost the coil. Since ASHPs can be used in many sizes for both heating and cooling the technology has a **High Scalability** rating, though a VRV system might be more suitable when it comes to installations on a larger scale. The ASHP is given a **High Implementability** rating since it is easy to install and can be installed anywhere, though with diminishing performance in cold climates.

### 5.2.3 VRV system - **Medium Scalability & High Implementability**

Being an air source system, the VRV system can be used in most climates and regions and does not require any specific geographical conditions. Since the VRV is a multi-split ASHP it can be used in air temperatures down to -15°C. The multi-split construction is scalable to many different applications, though the main application for the VRV system is in larger office complexes. The VRV system is essentially an ASHP designed for larger implementation. Considering this, we believe the VRV technology to be of **Medium Scalability**. The system is given a **High Implementability** rating, based on the fact that it is a well-known system (meaning installation and service is readily available) and easy to maintain.

### 5.2.4 Ground Source Heat Pump - **High Scalability & Medium Implementability**

Ground source heat pumps, or geothermal heat pumps can be used in all climates. However, the most suitable locations are where the heating and cooling demand over the year are fairly similar. This gives high efficiency over the year and prevents the need to let the ground recover from overheating or overcooling. However, it works just as well if it’s only used during parts of the year for one type of demand, since this also gives the ground time to recover.

The most demanding part of installing GSHPs is the cost. For the best use of a vertical GSHP, one must drill boreholes until the level where the temperature is fairly stable over the year is reached. This increases efficiency. This could require boreholes deeper than 100 meters which gives a high initial cost. Also, if the demand of heating and cooling is high, several boreholes have to be drilled. These can be positioned tightly, but doing so increases the necessary depth of the boreholes. Drilling costs per meter becomes more expensive the deeper the hole is (Berglund, 2013). For a horizontal GSHP the initial costs are usually lower, but for maximum efficiency the pipes need to be placed with such a distance between them that they don’t exchange heat. This requires a large space (around 500 m²), thus reducing the possibility to install horizontal GSHPs in urban areas. Being fairly demanding to install and requiring a large initial cost, though not comparable to the district heating systems, the GSHP is rated as **Medium Implementability**.

GSHPs can be used for both residential and commercial buildings, in small or large scale and this combined with the high degree of dimensionality adds to the scalability. Furthermore, as it’s been shown in the case studies, GSHPs have been used for many years in various locations and in different sizes, always displaying high performing. Taking this into consideration it can be concluded that GSHP has **High Scalability**.

### 5.2.5 Solar Assisted Heat Pump - **Medium Scalability & Medium Implementability**

Solar assisted heat pumps require a sunny climate, making the sunny belt of the Earth the ideal location for such technology. This limits the usage areas, although Wuxi would still be a good candidate. The SAHP could be implemented elsewhere and perform differently. It can function
well together with both an air or water source for space heating and might also have the ability to simultaneously heat water, thus increasing flexibility. The technology is not well implemented and not many products are on the market, reducing the possibility to implement it on a larger scale. However, the installation process is less demanding than a GSHP. It has been successfully implemented in the PIV-park in Shanghai, which argues that it might work at a larger scale. For these reasons the SAHP is given a Medium Scalability rating instead of low. It is believed to have Medium Implementability, being rather easy to install whilst still requiring a certain rooftop, or garden, area and climate to operate at full efficiency.

5.2.6 Dual Source Heat Pump - Low Scalability & High Implementability

A multifunctional heat pump (as the DSHP presented) has the advantage of quickly being able to switch between heating and cooling mode as well as produce domestic hot water. Water heating is something that most buildings require, both commercial and residential. Being dual source it can also use two types of heat sources, which gives it increased flexibility. However, just as with the SAHP technique, it has not been tested at a larger scale and is not well implemented. It’s unsure how well it could work in larger buildings such as offices. For the implementability however, it’s probably not difficult to connect it to two sources, including gray water since this is a bi-product from any household. For these reasons, the DSHP has High Implementability. Disregarding the fact that it’s an immature technique it might function well at a higher scale even though it hasn’t been tested. It would however be misleading to give it a medium scalability rating when no tests have been conducted on larger scale, therefore a Low Scalability rating is given.

5.2.7 Water Source Heat Pump - High Scalability & Low Implementability

A water source heat pump requires a near proximity to water in the form of a lake, sea, river etc. The quality of the water is not critical since a closed loop system can be utilized just as well as an open loop. In the cases we looked into, the buildings were of different sizes which indicate that water source heat pumps are applicable for buildings of dimensions, motivating a High Scalability. The areas of usage are many, as long as water is available. The downsides are the initial planning, prospecting and costs required to install a water source system, thus giving it the rating Medium Implementability overall.

However, in the case for Wuxi Eco-City drawing long pipes from each building to Lake Taihu would be ineffective. The solution would require a central solution. If the demand of the region is high enough it could motivate a smaller scale central heating/cooling system. Given that this is the only form of integrating WSHPs into the heating/cooling system of Wuxi the system is given a Low Implementability in Wuxi. It could be argued that the smaller rivers that run through the district are possible to utilize for laying the evaporator coils. Such a solution would, however, most likely bed for thermal encroachment, similar to the issue with tightly placed GSHPs.

5.3 Risk

Risk is the evaluation of the probabilities and consequences of undesired incidents. An example could be the solution showing a lower performance than expected, changing the attractiveness of that solution compared to others. The variability of performance, durability and implementability are what this parameter attempts to assess. Worth noting is that this parameter, as opposed to other parameters as performance and implementability, is more exposed to subjectivity. The
difficulty of quantifying risk in a comprehensive way encourages only a subjective evaluation of the relative risk each technology displays.

5.3.1 District Heating and Cooling - High Risk

The system that is built in Hammarby Sjöstad utilizes the water cleaning plants waste heat as a source for its heat production. Although the system is successful in Stockholm, replicating the system in Wuxi has high risk.

The size of the region is an important factor when considering a district heating/cooling solution. The question one must pose oneself is whether the demand is large enough to motivate the costs of laying the pipeline network. One could lay the pipe network simultaneously as the sewage, waste disposal and water lines thus lowering the costs. By seeking synergies one can bring down the costs, however the pipeline will remain a significant cost. This might contribute to a long payback time which could discourage investors, contributing to higher risk.

The unwillingness of the Chinese government to build centralized heating solutions in the south of China will further increase the risk of implementing such a heating/cooling solution. The city of Xiangtan in the Hunan province, south of the Yangtze, has implemented a district heating/cooling solution. However, no official announcements have been made concerning policy changes. Furthermore, Xiangtan is a city of 1 million inhabitants, which then has a significantly higher cooling demand than Wuxi Eco-City, with a smaller expected population.

5.3.2 Air Source Heat Pump - Low risk

ASHP has low risk. It has been implemented in many places of the world and is used extensively in the south of China (Chen et al., 2006). The performance is well known as well as how it is affected by the ambient temperature. In a climate such as Wuxi’s the high humidity might cause additional frosting which could further decrease the performance. This is however not significant enough since the temperatures in winter can rise above freezing during the day and thaw the frost periodically.

5.3.3 VRV system - Low Risk

The VRV system displays low risk. The concept has been market available for a time and the performance has been tested. The high performance of the system further ensures that developmental research and maintenance services will be available for the foreseeable future.

Furthermore, relatively low installation costs allow for good profitability and attract investors.

5.3.4 Ground Source Heat Pump - Low Risk

GSHP is mature technology and is known for its reliable performance. The risk increases slightly due to its high initial cost (relative ASHP, SAHP and the Multi-functional HP). There is a certain amount of uncertainty regarding the performance, which depends on the concentration of GSHPs in the area as well as the ground quality. These risks are easy to handle since the ground quality is verifiable before investing and the well spacing or loop spacing of the different units can be designed in such a way that the interference between units is minimized.

5.3.5 Solar Assisted Heat Pump - High Risk

Similar to the multi-functional heat pump discussed above, the SAHPs are still in the experimental phase of development. Compared to the multi-functional heat pump, a larger
amount of attention is being directed to SAHP development and there are now solar thermal assisted heat pumps coming out on the market (Kegel et al., 2012). Several constructions and more tests have been made concerning different ways of integrating solar thermal energy with heat pump technology. The constructions have had different uses and different performances.

Though there are models out on the market the novelty suggests high risk. That the big brands such as Sanyo, Fujitsu, Lennox and Daikin do not display any SAHP in their selections shows a lack of faith in the state of the technology. For these reasons the risk associated to SAHPs is high.

5.3.6 Dual Source Heat Pump- High Risk

The DSHP is still at the testing stage making it high risk technology. Little is known about the performance, the durability and the dimensioning. The sample size is small and the construction has only been tested in one location, with one size, with one set of parameters and in two out or four working modes. Collectively these contribute to a high risk. One could argue that the components that constitute the system are all market available, which would hint at a lower maintenance and dimensioning risk. The component risk is minimized by standardization, yet the system risk lies in their collective performance and durability, which cannot be guaranteed by other means than testing.

5.3.7 Water Source Heat Pump – Medium Risk

Similar to the GSHP, the WSHP is mature technology with a reliable performance. The risk will vary depending on whether the system is open loop or closed loop. Open loop systems have an increased risk of damaging the compressor by having it come in contact with ice or other materials (e.g. algae). The WSHP can, as the GSHP, encroach on the performance of each other if too closely spaced and the water temperatures are central for performance estimation. These factors are, as with the GSHP, easily soothed through investigation of the water body

Furthermore, regulations restrict the use of lakes (which is relevant in the case relating to Wuxi) for heating/cooling purposes. This is in order to care for the lakes internal environment. The well being of the lake is important in the Wuxi region. Billions of dollars have been invested in cleaning the lake, any activity that can be seen as potentially harmful for the lake will thereby be prohibited. A closed loop system would cause little or no harm to the lake, lowering its risk.
6 Summary of Solution Evaluation

The analysis of the four parameters performance, scalability, implementability, and risk (See Fig. 10) produces two distinct groups of techniques, which display similar feasibility. One is a group with district heating, solar assisted heat pumps, and dual source heat pumps (See Fig. 11). These three techniques display poor evaluation results in two or more parameters. The other group consists of air source, ground source, and water source heat pumps as well as the variable refrigerant volume system (See Fig. 12). These technologies showed, on average, good results on the evaluated parameters.

Based on these results, dual source heat pumps (DSHP), solar assisted heat pumps (SAHP), and district heating (DH) will be disregarded as possible heating and cooling solutions for Wuxi Eco-City. They have proved to be inappropriate in the current context, considering that the building of an eco-city is a major project and in such a case any implemented solutions should be optimized and reliable.

SAHP and DSHP are both immature technologies that might have good future prospects but lack a reliable track record to motivate a large-scale installation. At the current stage they are uncertain and without best practices, making the investment too risky.

District heating on the other side is a well-known solution for covering the heating/cooling demand of a large area. This technology has got disadvantages as well, the major concerns here are that the Chinese government has a policy against district heating solutions in south China, that the demand needs to be large enough to motivate such a system (low scalability), and that the water in Lake Taihu might not be optimal for a large system based on this solution. Another issue might also arise when it comes to combining heating and cooling into the same system. It is possible to run it in the same system using radiators (Frederiksen et al., 2011) but usually it’s distributed in separate pipeline systems. This is the case for example in Toronto where cooling is drawn from Lake Ontario (Enwave, 2013-a), and heating from steam plants (Enwave, 2013-b). This would potentially double the pipeline network costs, further increasing the difficulty of implementation. However, a small district heating system utilizing Lake Taihu is still considered as a possibility.

The techniques WSHP, GSHP, VRV and ASHP are all possible heating and cooling solutions in Wuxi Eco-City. The STELLA simulation of the energy demand for heating and cooling will therefore consist of these four solutions. The performances of the remaining solutions obtained here will be illustrated with a STELLA simulation. The solutions will be assessed from the sustainability triangle perspective before a final suggestion of the most suitable solution(s) is presented.
Figure 10 - Evaluation results. District heating and cooling (DH), Air source heat pump (ASHP), Variable refrigerant volume (VRV), Ground source heat pump (GSHP), Solar assisted heat pump (SAHP), Dual source heat pump (DSHP), Water source heat pump (WSHP)

Figure 11 - Techniques showing poor evaluation results

Figure 12 - Techniques showing promising evaluation results
7 The Sustainability Triangle Perspective

7.1 Air Source Heat Pumps

Out of an environmental perspective, ASHPs have no observed effects. The system is clean, and doesn’t impact the surroundings more than the obstruction of the heat pump itself. The biggest potential environmental threat that an ASHP possess is the carbon emission of the electricity used to run the heat pump. Since the ASHPs have lower COPs than the other heat pumps, this is not negligible in a country with a high ratio of electricity production from fossil fuels.

From an economic point of view, ASHPs are good because they are cheaper than heat pumps using other sources. Their lower COPs, on the other hand, make for higher electricity consumption. Before installation, an analysis of the payback time is required.

ASHPs make a slight noise when they are on, and this could have an impact socially if they are installed where desired sound levels are low. It’s also possible that installation on rooftops could take up valuable space that could be used for solar panels, relaxation or greenhouse areas (Thornton, 2010). Another point that Helmer et al. point out, is that open installations of ASHPs face the threat of vandalism (Helmer et al., 2010).

7.2 Variable Refrigeration Volume

The triangle analysis of VRV is similar to the previous analysis of ASHP. However, VRV systems require a large amount of refrigerant which if leaked could have substantial environmental effects (Horsley, 2010).

The installation of a VRV system doesn’t necessarily become more expensive than an ASHP installation. It all depends on the system size, since a large heating/cooling demand would alternatively be met with several ASHPs. The technical advantages that VRV has over ASHP might be costlier initially but over the long run the VRV system with a generally higher COP will have less total energy demand, and thus costs. Also, VRV is supposed to have low maintenance costs.

Socially, VRV systems provide a higher value of standard than other heat pump systems. It can be combined with the ventilation system to provide an even higher level of comfort, and can be regulated locally in the building for different preferences. They can however, when old, become noisy and thus require a periodical renovation of the system (Horsley, 2010).

7.3 Ground Source Heat Pumps

Since the ground is affected to some extent when a GSHP is installed, they have possible environmental effects. In Germany the drilling of seven boreholes for ground source heat pumps caused severe damage to the surrounding city due to height shifts of the land, triggered by the drill (Burbaum & Sass, 2010). Another threat is that of the ground temperature being affected over time if used unevenly or if not given time to stabilize after a season in use.

Also, there is the threat of damaging circulation fluids, such as antifreeze solutions, being released into the ground (Mehnert, 2004). Another report states that aggressively rooting species should be removed before installation to prevent them weakening the pipes (Arkins, 2004).
Ground water as a source could cause several geological problems if the water is over-exploited. One example in that was unknown before it actually happened was in Germany where the land subsidence changed because it wasn’t controlled (Deng, 2007).

When considering installation, vertical or horizontal GSHPs are possibilities. Vertical is better if the value of the land is high since this technique does not utilize as much area as a horizontal GSHP. Furthermore, the shallow soil has a higher rate of temperature change, meaning longer pipes are required than in a vertical installation (Arkins, 2004). Before installation, this requires an economical study of drill costs and pipe installation as well of the expected payback from the higher performance compared to other heat pumps.

From a social aspect, GSHPs are superior to ASHPs because of their invisibility to the user. As earlier mentioned there is always a risk of vandalism for ASHPs. However, horizontal heat pumps cause restrictions of soil usage in the installation area which could cause a problem for future constructions.

### 7.4 Water Source Heat Pumps

There is the risk, when using WSHPs, that polluting substances leak out into the water. In an open loop system the pipes can corrode bringing rust into the water source or insufficient filtration could cause negative effects on the water (EGSHPA, 2011).

WSHPs are generally cheaper to install than GSHPs but more expensive than ASHPs (Renewable Energy Advisor, n.d.). This makes a payback analysis more important than for an ASHP since the risk increases with higher investment costs.

Similarly to GSHPs this technique is, unless it has affects on a nearby body of water or requires maintenance, rather hidden which causes it to have minimal social effects.

A summary of this section is given in table 2.
<table>
<thead>
<tr>
<th>System</th>
<th>Environmental</th>
<th>Economical</th>
<th>Social</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASHP</td>
<td>++ Clean and doesn’t impact surroundings - To a higher degree exposed to electricity from fossil fuels due to low COP.</td>
<td>++ Lower initial costs than other heat pumps - - Higher electricity consumption</td>
<td>- Make slight amount of noise - Might take up valuable space - Could be subject to vandalism</td>
</tr>
<tr>
<td>VRV</td>
<td>- Require large amount of refrigerant which risk being leaked</td>
<td>+ Low maintenance costs despite size + Low electricity consumption - Higher initial costs than ASHP</td>
<td>++ Provides a high level of comfort due to better regulation capabilities - Might be noisy when the system becomes old</td>
</tr>
<tr>
<td>GSHP</td>
<td>- Affects ground by drilling and temperature shifts - Damaging refrigerants could be released into the ground - Pipes are exposed to aggressively rooting species</td>
<td>++ High and stable performance which cause low electricity consumption +/- Is dependent on an analysis to evaluate whether vertical or horizontal pipes are preferable - - High initial costs which makes payback analysis important</td>
<td>+ Invisible to user - Horizontal installations might affect future installations</td>
</tr>
<tr>
<td>WSHP</td>
<td>- Polluting substances could leak into the water - With open loop systems polluting risks are higher</td>
<td>+/- Generally cheaper to install than GSHPs but more expensive than ASHPs - - Substantial initial costs which makes payback analysis important</td>
<td>+ Is hidden and has minimal social effects</td>
</tr>
</tbody>
</table>

Table 2 – Summary of sustainability triangle perspective. The short notes are coupled with one or two “+” or “-”, or both, to denote a positive or negative attribute.
8 Simulation Results

The following material is presented for visualization purposes only. Tables 2 and 3 display the variables used in the model for generating scenarios and for calculating annual energy utilizations.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Ideal COP1 or SPF1</th>
<th>Ideal COP2 or SPF2</th>
<th>Variance (%/delta Temp)</th>
<th>Min COP</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASHP</td>
<td>4</td>
<td>3,2</td>
<td>3%</td>
<td>1,5</td>
</tr>
<tr>
<td>VRV</td>
<td>5,5</td>
<td>5</td>
<td>3%</td>
<td>2</td>
</tr>
<tr>
<td>GSHP</td>
<td>4,6</td>
<td>4,2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WSHP</td>
<td>4,2</td>
<td>4,2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3 – Technology specific parameters. The GSHP and WSHP do not vary with the atmospheric temperature and were approximated with SPF values instead as discussed in the assumptions section above.

<table>
<thead>
<tr>
<th>Other Parameters</th>
<th>Not technology specific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q High End Performance</td>
<td>Varies hourly</td>
</tr>
<tr>
<td>Q Good Performance</td>
<td>Varies hourly</td>
</tr>
<tr>
<td>Q Standard Performance</td>
<td>Varies hourly</td>
</tr>
<tr>
<td>Lowest Indoor temperature</td>
<td>20</td>
</tr>
<tr>
<td>Highest Indoor temperature</td>
<td>24</td>
</tr>
<tr>
<td>Temp</td>
<td>Varies hourly</td>
</tr>
</tbody>
</table>

Table 4 – Variables that are general for all technologies.

The simulation results show that the technologies that have a larger variance in their performance (ASHP and VRV) display larger energy usage for the modeled year (See Fig. 13 and 14). The larger variance is because of the temperature dependent performance, which becomes lower when the temperature difference between outdoor temperature and heat pump working temperature becomes higher. GSHP and WSHP display a smaller energy usage and this is because they have less variance in their performance (See Fig. 15 and 16).

For all the technologies there are well-defined periods of high activity and others of next to no activity. This is due to the range for acceptable indoor temperatures, which spans from 20° C to 24° C. During certain periods the temperatures naturally vary within the range (the ranges with low/no activity) and thus there is little need for using the heating/cooling system. The middle region of high activity represents the summer months and is thus the energy used for cooling purposes. The other two regions, in the beginning and end of the year, represent the periods of heating.
Figure 13 - The Energy Utilization (kWh) for ASHP. Energy utilization (in kWh, displayed in red) of one High End, one Good standard and one Standard building, using ASHPs, as it varies with the ambient temperature (in °C, displayed in blue). The graph is without max power.

Figure 14 - The Energy Utilization (kWh) for VRV. Energy utilization (in kWh, displayed in red) of one High End, one Good standard and one Standard building, using VRV, as it varies with the ambient temperature (in °C, displayed in blue). The graph is without max power.
**Figure 15 - The Energy Utilization (kWh) for GSHP.** Energy utilization (in kWh, displayed in red) of one High End, one Good standard and one Standard building, using GSHPs, as it varies with the ambient temperature (in °C, displayed in blue). The graph is without max power.

**Figure 16 - The Energy Utilization (kWh) for WSHP.** Energy utilization (in kWh, displayed in red) of one High End, one Good standard and one Standard building, using WSHPs, as it varies with the ambient temperature (in °C, displayed in blue). The graph is without max power.
The pattern is also made visible through a cumulative graph of the hourly energy usage for the whole year (See Fig. 17). In this graph it’s clear that the ASHP technology is the highest consumer of energy. This is because of a generally lower performance and a high dependence of outdoor temperature. ASHPs actually seem to use twice the energy over a year compared to GSHP and WSHP. Moreover, GSHP and WSHP have very similar energy utilization and this is because these technologies have no varied performance because of stable source temperatures. In actuality, water sources do have temperature fluctuations that affect performance. These are not of the same magnitude as air source and thus the use of an average performance can be justified.

Figure 17 - The relative energy usage (in kWh) of the different technologies. Illustrated with one of each building type, run with hourly data throughout a one-year period

8.1 Selection of Sensitivity Analysis Results

Below follows a selection of results from the sensitivity analysis. The diagrams consist of changes in the model regarding a standard building. The first diagram (See Fig. 18) displays varying SPF and Ideal COP for the four techniques.

As was seen in Figure 17, this diagram shows that GSHP is the most conservative solution with regard to energy use, and ASHP the technology with highest energy use. The ASHP technology with increased Ideal COP is using substantially more energy than the GSHP with reduced SPF. The difference between SPF1/COP1 and SPF2/COP2 is lowest for GSHP.

The possibility for error in the performance estimation is real, however an increase of 1, in ideal COP or SPF, is a substantial difference and is deemed as unlikely. Technologies with similar performances could however switch ranking in performance due to the uncertainty involved. On the other hand, the GSHP remains the technology with lowest variation in source temperature, which allows for more stable performance over the whole year.
The second diagram (See Fig. 19) displays varying Variance and varying Minimum COP for the VRV and ASHP techniques (which were the techniques that where these parameters were most applicable). Increasing the variance causes higher energy use. Increasing the minimum COP reduces the energy use for both technologies, though only marginally.

See Appendix B for further information, including sensitivity analysis of a good standard building and a high end building.

**Figure 18 - Varying SPF and Ideal COP for a standard building.** GSHP displays the lowest overall energy use.

**Figure 19 - Varying Variance and Min COP for a standard building.** Varying the variance has a greater impact than varying the min COP.
9 Discussion

The considered solutions were narrowed down during the evaluation of the possible solutions. Using biogas as fuel for the heating/cooling system was ruled out when the district heating solution was discarded, since the remaining solutions operate using electricity.

The water and ground source heat pumps (WSHP, GSHP) are both high performing. They are applicable on all sorts of buildings. To have WSHPs installed in all buildings and with individual source-feeds in Lake Taihu would be inefficient and likely detrimental to the performance. Due to the heat conduction in the pipes on the way to the heat pump, long pipes are not beneficial. Thus the only feasible water source solution would be to build, as in Xiangtan, a minor central heating and cooling system with several WSHPs.

In order to ascertain whether a minor central solution is beneficial, the costs of the network (to the end-users that it will reach) would have to be estimated and the demand verified to be large enough to regain the investment costs within a reasonable time limit. Further difficulties are, as mentioned earlier, whether Chinese governmental policy would allow a minor central heating and cooling solution, particularly one that utilizes water from Lake Taihu. Lake Taihu has large issues with algae blooms during the summer; whether this affects the performance or maintenance costs is another factor to be considered before commencing any construction. The Mengze Lake near Xiangtan is, as Lake Taihu, victim to large algae blooms. Whether the extents of the blooms are equal to those of Lake Taihu is uncertain and would have to be investigated in order to estimate the expected end performance of a similar centralized solution as in Mengze Lake. In short, if a water source solution is considered of interest, then a central solution will be needed and further research concerning the effects of the algae blooms, the costs of the network, the demand, the policy concerning district solutions and the potential effects on the lake, has to be made. An evaluation of the maximum effect a central solution could obtain, given the size and depth of Lake Taihu, is needed. These investigations would contribute to the price of the solution as sunk costs. This solution is less attractive as it carries many of the same disadvantages as traditional district heating.

The vertical ground source solution is applicable, in decentralized form, to nearly all sizes of buildings. For a ground source the costs of the borehole drilling as well as the possible effects on the ground need to be investigated. A thermal response test to check the conductivity of the earth would need to be made in order to see how deep the boreholes need to be. The difficulty with the GSHP is the spacing between boreholes and the density of the demand so as to prevent thermal encroachment or rises of the ground's average temperature. The ground temperature should be monitored to prevent this, but in Wuxi where the heating and cooling demands are fairly similar the soil temperature should remain balanced, even over extended periods of time. This could, however, depend on the type of building that was constructed.

The GSHP technology is well-known in Sweden, and manufactured by the three largest heat pump companies in Sweden; IVT, Nibe, and Thermia. It has been shown to have a high performance, and since the heating and cooling demand in Wuxi is fairly similar there is a small to no risk of doing long-term harm to the ground.

Moreover, the technology is suitable for usage in urban environments with dense city planning since the boreholes are drilled vertically into the ground. If the heating and cooling demand is high in a narrow area, the boreholes can be made deeper for increased thermal extraction. It's also possible to drill several boreholes connecting to the same heat pump if the demand is high.
In Sweden a distance of 20 meters between each borehole is recommended but it’s possible to narrow the distance by using tilted drilling and measuring between the middle points of the boreholes. It’s also possible to put the boreholes closer together by drilling deeper into the soil, but this might become economically inefficient since the costs of drilling increases with the depth (Berglund, 2013).

Air source heat pumps (ASHP), as previously discussed, are easy to implement, cheap and common. They do however exhibit lower performance and make a slight amount of noise. The noise should not be too large an issue though. The ASHP is the optimal solution for passive houses that require little heating and cooling and are of a smaller size. Passive houses seem to have a lower heating and cooling demand (Engdahl & Wallgren, 2013), compared to a standard house, and might not have a high enough demand to make any larger investment, such as GSHPs, economically viable.

Variable refrigerant volume systems (VRV) are easily maintained and suitable for offices and commercial buildings because they can provide a high level of control and comfort. The efficiency of the technique is not as stable as GSHPs but it could be preferred over GSHP in some cases if the desired levels of comforts are higher. This would weigh the social aspect over the economic aspect as running a VRV system could become more expensive in the long run.

9.1 Critical Analysis of Data

The data collected is varying in quality. Amongst the reasons for this are availability of information, the interpretation (amongst the authors) of terms such as EER, the methods for assessing performances and the dates of publication.

For certain heat pump technologies there has been more information available than for others. The case studies for ground source heat pumps have been many whilst case studies for WSHPs and VRVs have been few. This affects the certainty of any evaluation in performance. It can be explained by unpopularity or by novelty of the technology. In the case of VRV systems, the performance is difficult to measure since there are many factors that contribute to the performance and that vary between implementations.

Many of the results found concerning performance, particularly when researching the market available heat pumps, showed large variations in SEER and EER values. EER is a measurement of performance in BTU/h (British Thermal Units) per kWh electricity. Although, in many cases the SEER displayed a magnitude suggesting such a unit was used, equally often it seemed to be a misinterpretation. This data was used when considered reliable and otherwise disregarded.

When the interpretation was correct, the numbers could nonetheless display a large variance. When studying the fine-print of the different technical data sheets, the conditions under which the performance was attained could vary and were at times manipulated. As a consequence a lot of data was discarded. This was particularly true for ASHPs where the COPs are insipid, since they only display the performance for one set of conditions.

The dates of the different publications were taken into consideration when evaluating the reliability of the data. In most cases, current data could be found and the older data omitted from the study.

Despite any uncertainties, the majority of the data is considered to be sound and applicable in the analysis of the different solutions.
9.1.1 Critical Analysis of Modeling Data

The input data for the model contains considerable uncertainty. The weather data can be assumed to be typical of the Wuxi region. However, the COP, SPF and variance values used contained considerable uncertainty. The effects of this are investigated in the sensitivity analysis (See Appendix B). An increase, or decrease, of 1 in the SPF or COP values affects the energy utilization with between 7-15%. This can mean that the relative energy efficiency of the different solutions could change, making other solutions more beneficial than the suggested. The risk is that by overstating the one solution’s performance, whilst simultaneously understating the others’ could lead to a suboptimal solution and an inaccurate scenario. Nevertheless, this is unlikely since an increase/decrease of 1 is a large difference. Furthermore, the data provided as to the building performance are also subject to levels of uncertainty.

The scenario provided in this study is only a preliminary estimate given a certain amount of buildings. The model is unbiased to new data and is adjustable to create further scenarios.
10 Suggested Solution for Wuxi Eco-City

There are two possible solutions that have shown to be advantageous over the others. The primary suggestion for residential and commercial buildings is to use vertical ground source heat pumps for most buildings. An economic calculation should be made beforehand to examine if it’s more beneficial to install air source heat pumps or variable refrigerant volume systems in high end buildings with low total demand. A GSHP requires a larger initial investment and thus might not be suitable to the most efficient buildings. Depending on time horizon, such a solution could prove to be cheaper. An alternative solution is to use a minor centralized heating and cooling system with the nearby Lake Taihu as heat source/sink, though this solution carries many of the investment costs of a traditional district solution.

The solution for heating and cooling that is most likely to be viable in Wuxi Eco-City, the primary suggestion, is the installation of GSHPs. GSHPs are the best solution for installation in buildings with high cooling and heating demand. For passive buildings, ASHPs could be a better solution because of lower initial costs. VRV systems could be a better solution in larger office and commercial buildings, because of the high level of comfort the systems bring.

The advantageous aspects of using vertical ground source heat pumps are:

- A well-known solution, especially in Sweden
- Showing reliable efficiency
- Suitable for urban usage
- Capable to handle high heating and cooling demand
- A long-term economic solution
- Sustainable and has low environmental impact

The most important criteria for the usage of GSHPs in Wuxi Eco-City, is the reliable efficiency of the system. Moreover, the initial costs for ground source heat pumps are high but can be compensated by the annual savings. A basic economic analysis would show that the payback time decreases with higher annual heating and cooling load for a ground source heat pump. The same analysis on an air source heat pump would also show that the payback time increases with a higher demand, though for low demand throughout the year an air source heat pump would have an even lower payback time than a GSHP. This does not necessarily mean that ASHPs are preferable, because heat pumps are normally installed for use during longer periods of time, and in the long run a GSHP with superior COP to an ASHP will save more money. However, raising capital for a longer-term investment might prove to be difficult, causing ASHP to be the favorable choice for low annual heating and cooling demand.

The building types presented here might differ from the actual constructed buildings and the properties of these should be examined before any final decision about heat pump technology is made. For dimensioning of the heat pumps building properties such as isolation, internal gains, window area, and resident behavior should be measured and examined in order to approximate the heating and cooling load over the year.

Furthermore, municipal guidelines should be examined to determine if any laws or regulations could prohibit the installation or drilling of GSHPs.

Utilizing the nearby Lake Taihu and constructing a minor centralized heating and cooling system consisting of several water source heat pumps as in Xiangtan is an alternative solution for Wuxi.
Eco-City. This solution is however dependant on the exact distance to the lake, because piping long distances quickly becomes expensive. It is dependent on the absence of regulations that might inhibit central heating systems. An opportunity could be to partly install a minor central heating and cooling system for the buildings closest to the lake, and use GSHPs for the rest of the buildings. This would require a thorough economical analysis to examine the size of the system. Furthermore, the exact extent of regulations, effects on algae blooms and potential lake effects should be researched before going on with such an implementation. Further research should be conducted to confirm the expected performance of such a system.
11 Scenario

In this section a possible scenario using GSHPs in Wuxi Eco-City will be simulated using STELLA.

The scenario given here provides an estimate of the energy usage for the residential district given that there are 20 of each building type. The standard and the good standard buildings utilize the GSHP technology and the High End building utilizes ASHPs. The reason for this is that the High End houses have a lower utilization, making a GSHP excessive due to its implementation costs.

Given these premises, the yearly energy utilization for the residential sector of Wuxi Eco-City is 1822 MWh of electricity (See Fig. 20).

![Figure 20 - Total annual energy utilization (kWh) for the residential sector](image)
12 Conclusion

In this report solutions for the heating/cooling system in Wuxi Eco-City have been analyzed as to their feasibility in order to ascertain which would be the most favorable solution. The different technologies have been evaluated from the point of performance, risk, implementability and scalability. Solutions that were found to be less feasible were omitted from the next step of evaluation. The remaining solutions were analyzed using “The Sustainability Triangle” and simulated in a model (developed using STELLA) to visualize their relative performance.

- The GSHP technology is deemed the most appropriate solution for Wuxi Eco-City. A scenario of the residential district in Wuxi Eco-City was simulated, using the suggested solution, and the estimated annual energy usage was 1822 MWh.

- Further economic analyses of the cases when the annual heating/cooling load is low should be made to determine if there are cases in which an ASHP or a VRV system should be preferred.

- An alternative suggestion is to implement a minor centralized heating and cooling system using WSHPs. Studies should be performed concerning effect on Lake Taihu, economic viability, and expected performance before an implementation.

Through the course of the study, innovative heat pump solutions were discovered. These technologies were deemed inappropriate for implementation in Wuxi Eco-City but could be interesting for further study.
13 Suggestions for Future Research

The suggested solution for Wuxi Eco-City requires the following investigation before implementation.

- The ground characteristics and the resulting borehole depth requirement
- A thorough economic analysis of the GSHP given the installation costs, electricity costs and other factors that are decisive for such an analysis. This is in order to verify that a GSHP is the most beneficial solution.

The following is a list of possible future studies that tangent this report.

- “Life cycle analysis” comparisons between heat pump technologies
  Other factors than performance affect the total benefits of a heat pump. Example of questions could be: How does a GSHP perform in form of energy usage compared to an ASHP? What are the costs (energy, CO₂, economic, environmental impact) to install and maintain a GSHP over a period of 10 years? What is the comparative carbon impact between the heat pumps?

- Economic analysis of GSHPs in the Chinese climate
  Given the total energy demand in this report’s scenario, or energy demand based on another Wuxi Eco-City scenario, a deeper economic analysis of the costs of installing GSHPs could be made. Examination areas could be payback time or comparison to electric heating. Is there a certain electricity price at where it’s actually better to install electric heaters, due to a long payback period for heat pumps? Could such a low electricity price occur? This analysis could be made within another area too.

- An economic analysis of ASHPs compared to GSHPs
  As stated in this report, there might be an advantage to installing ASHPs over GSHPs if the total heating and cooling demand is low for a building. The reason might be that the building is a well-insulated, so-called passive house. ASHPs are cheaper to install than GSHPs. If the gain from installing a ground source heat pump is low the payback time could be too long to motivate an investment. With a cheaper installation cost, such an investment could be motivated with an ASHP.
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Appendix A – Model overview

Appendix A.1. The model is constructed in layers where data, such as the Q loads of the different buildings, is inputted into the model and sent into each technology module. These modules then return the energy usage, categorized by building. This creates a matrix of utilization data and can be summed to get the total energy utilization for the entire district. The total energy utilization is given in the same units as the inputted Q. The model is adaptable in order to create new scenarios with new data.
Appendix A.2. Each module treats the different buildings separately. The data is converted, through the COP, into the energy that is utilized for the heating/cooling (The model considers a negative Q value to be cooling load and a positive Q value to be heating load). A max effect per building can be stated and the resulting percentage of the load covered will allow dimensioning. This parameter and the parameters affecting the COP are all adjustable.
Appendix B – Sensitivity Analysis

For GSHPs and WSHPs differences of 1 in SPF values affect the energy usage of the buildings by between 8-15%. It is however to be noted that an increase/decrease of 1 in SPF is a significant change. The equivalent percentage change for VRV, according to the model, is between 7-12% and 10-18% for ASHPs. This shows a greater variability, typical for ASHPs.

<table>
<thead>
<tr>
<th>WSHP</th>
<th>SPF1</th>
<th>SPF2</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>3.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Energy consumed per High End Building</td>
<td>20670</td>
<td>18388</td>
</tr>
<tr>
<td>Energy consumed per Good Standard Building</td>
<td>35734</td>
<td>30353</td>
</tr>
<tr>
<td>Energy consumed per Standard Building</td>
<td>39036</td>
<td>32982</td>
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</table>

Percentage fluctuation (average percentage change per SPF step of 1)

-75-
<table>
<thead>
<tr>
<th></th>
<th>SPF1</th>
<th>SPF2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSHP</td>
<td>Percentage Fluctuation</td>
<td>Percentage fluctuation</td>
</tr>
<tr>
<td></td>
<td>(average percentage change</td>
<td>(average percentage change</td>
</tr>
<tr>
<td></td>
<td>per SPF step of 1)</td>
<td>per SPF step of 1)</td>
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<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>3.6</td>
<td>4.6</td>
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<td>17753</td>
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<td>28446</td>
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<tr>
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<td>36210</td>
<td>31297</td>
</tr>
<tr>
<td>VRV</td>
<td>COP 1</td>
<td>COP 2</td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Energy consumed per High End Building</td>
<td>23424</td>
<td>21411</td>
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<tr>
<td>Energy consumed per Good Standard Building</td>
<td>41570</td>
<td>36762</td>
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<tr>
<td>Energy consumed per Standard Building</td>
<td>45561</td>
<td>40161</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5</td>
</tr>
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<td>Energy consumed per High End Building</td>
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<td>21411</td>
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<tr>
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<tr>
<td>ASHP</td>
<td>Ideal COP1</td>
<td>Percentage fluctuation (average percentage change per SPF step of 1)</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
<td>---------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4</td>
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<tr>
<td>Energy consumed per High End Building</td>
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<td>60916</td>
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<td>Energy consumed per Standard Building</td>
<td>68652</td>
<td>58358</td>
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<table>
<thead>
<tr>
<th>ASHP</th>
<th>Ideal COP2</th>
<th>Percentage fluctuation (average percentage change per SPF step of 1)</th>
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<tr>
<td></td>
<td>2.2</td>
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<td>Energy consumed per High End Building</td>
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<tr>
<td>Energy consumed per Good Standard Building</td>
<td>60686</td>
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<tr>
<td>Energy consumed per Standard Building</td>
<td>67679</td>
<td>58358</td>
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</table>
The minimum COP cap for VRV systems and ASHPs affect the performance only marginally when set to vary with 1 from a baseline of 2 and 1.5 respectively.

<table>
<thead>
<tr>
<th>VRV</th>
<th>Min COP</th>
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<tr>
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<td>Energy consumed per High End Building</td>
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<td>Energy consumed per Good Standard Building</td>
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<table>
<thead>
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<th>ASHP</th>
<th>Min COP</th>
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<td>Energy consumed per High End Building</td>
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<td>31384</td>
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<tr>
<td>Energy consumed per Good Standard Building</td>
<td>52583</td>
<td>51964</td>
</tr>
<tr>
<td>Energy consumed per Standard Building</td>
<td>59094</td>
<td>58358</td>
</tr>
</tbody>
</table>
The variance is measured as the percentage change (expressed as a decimal) of the COP for each degree increase of the source-sink temperature difference. The variance displays a large importance when considering energy usage. A one percent increase of the variance signifies, on average, a 12% increase in energy usage for the ASHP and VRV technologies.

<table>
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<th>0.05</th>
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<th>Percentage fluctuation per percentage of variance</th>
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<td><strong>ASHP</strong></td>
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